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Geothermal energy – A geological contribution to the energy transition

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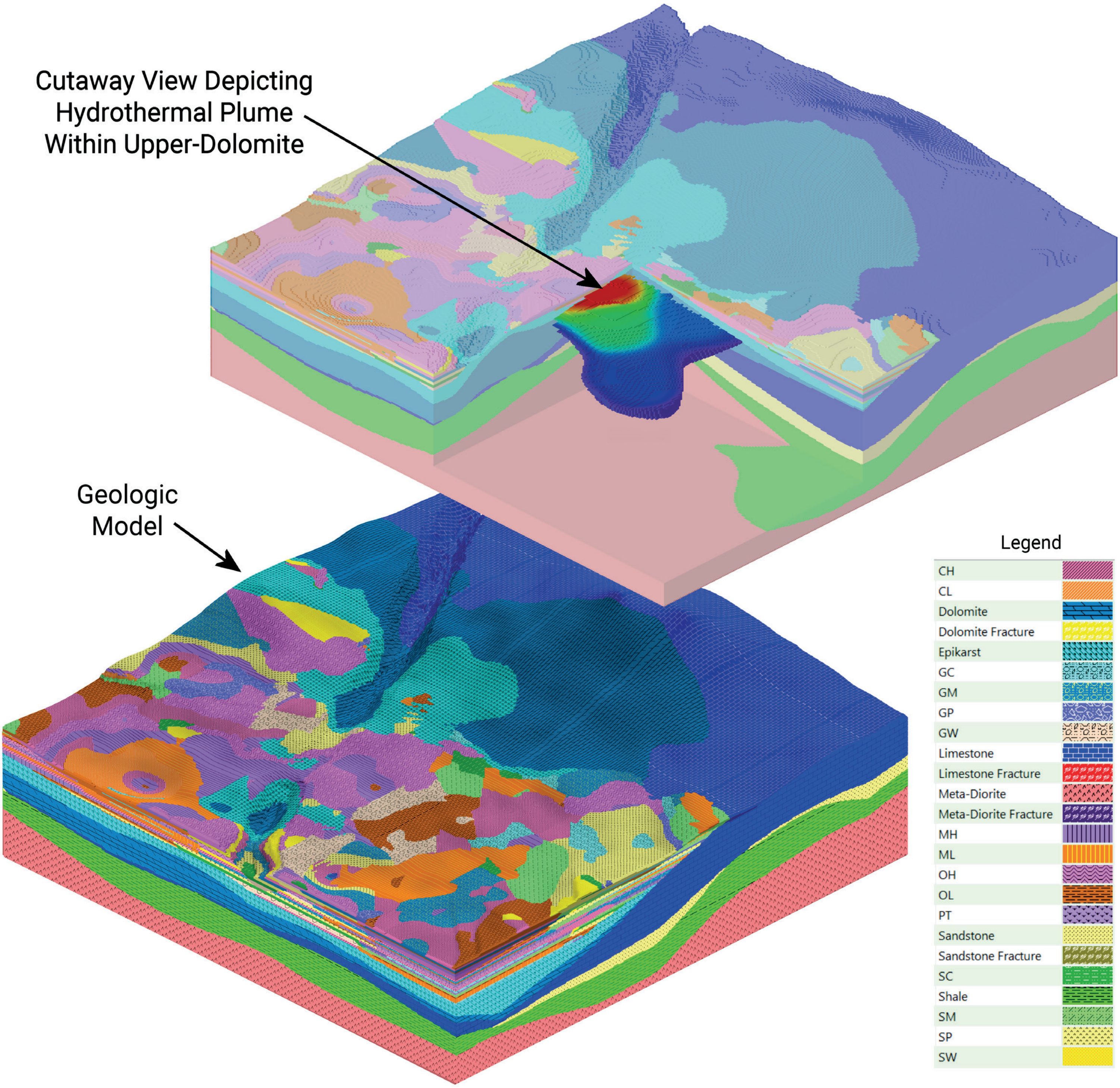

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Peer review:
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Foreword

EurGeol. Marko Komac, EFG President

Dear Reader,

Welcome again to your favourite professional geologist's journal! You're holding in your hands the 54th edition of the *European Geologist*!

Challenges that modern society faces are mainly related to energy. After all, it's the "source" of any movement, any travel, any heating (or cooling!). Traditional carbon-based sources of energy are obsolete due to their inefficiency and devastating environmental footprint. It is upon geological and geoscientific domains to address these issues in their best capabilities. After all, there are numerous natural energy sources around us that general public and with it the society don't even notice. One such resource is the geothermal potential that's widely used for traditional spa purposes, yet its potential is much wider and bigger. Geologists are aware of it and seek new vehicles to exploit this almost limitless source of energy to its highest potential.

As you'll be able to discover in this issue of *European Geologist*, several geothermal-related projects are ongoing, mainly financed by the European Horizon 2020 research funds. We bring you a plethora of topics in this intriguing field – from exploring and exploiting deep geothermal resources, optimising its use in heating/cooling systems, and using community-based financing to minimise or distribute costs, to the public perception of novel applications of such energy source. We also tried to bring you a territorial variety of approaches, not focusing only on European soil, but also looking beyond the continent's margins, to Costa Rica and Canada. By doing so, we've shown that the challenges of geothermal resources are universal, yet always a bit specific, and that addressing them needs cooperation, knowledge-sharing and good and reliable local data.

Success in finding novel solutions in exploiting Earth's geothermal potential brings new possibilities for the European's Green Deal goals and will – with adequate financing – help ease the transition to the non-carbon energy sources. The benefit of these results not only help Europe on its path to the greener future, but also enable other worldwide users to follow.

Indeed, the future can and will be green. I'm certain that it will be, among other shades of green, also "steaming green". I wish you interesting moments while reading the latest edition of the *European Geologist* and in the name of all the EFG family I wish you a healthy, happy, peaceful, and prosperous 2023!

Marko Komac

Geothermal use and potential of the Lund Sandstone in SW Skåne, Sweden

Mikael Erlström[1,2,] and Jan-Erik Rosberg[3]*

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The Cretaceous Lund Sandstone has been used as a geothermal resource by the city of Lund since the mid 1980s. A geothermal plant has provided up to 350 GWh/year from the c. 20 °C reservoir, corresponding to up to 45% of the heating demand in the city. The operational experiences serve as a unique reference for further exploration. The heat in place is estimated to correspond to several hundred years of heat consumption for five urban areas with about 300,000 inhabitants. The heat storage potential is also substantial and highly interesting for further exploration. Illustrating the heat reserve and the storage potential will hopefully foster further use of the resource, provided there are feasible competitive technical solutions.

Le grès de Lund du Crétacé est utilisé comme ressource géothermique par la ville de Lund depuis le milieu des années 1980. Une centrale géothermique a fourni jusqu'à 350 GWh/an à partir du réservoir à ca. 20 °C, ce qui correspond jusqu'à 45 % de la demande de chauffage de la ville. Les expériences opérationnelles servent de référence unique pour une exploration plus approfondie. La chaleur en place est estimée à plusieurs centaines d'années de consommation de chaleur pour cinq agglomérations d'environ 300 000 habitants. Le potentiel de stockage de chaleur est également substantiel et très intéressant pour une exploration plus approfondie. Illustrer la réserve de chaleur et le potentiel de stockage favorisera, espérons-le, une utilisation ultérieure de la ressource, à condition qu'il existe des solutions techniques compétitives réalisables.

La formación Lund se ha utilizado como fuente geotérmica por la ciudad de Lund desde mediado de los 80´s. La planta Geotérmica ha generado hasta 350GWh/año desde el reservorio a temperatura 20 °C lo que ha correspondido en hasta un 45% de la demanda de calor de la ciudad. Las experiencias operacionales han servido como autentica referencia para la futuras exploraciones. El calor in situm se estima que puede corresponder a cientos de años de consumo de calor, para cinco áreas urbanas con aproximadamente 300.000 habitantes. El potencial de calor almacenado es significativamente elevado e interesante para futuras exploraciones. Es de esperar que ilustrar las reservas de calor y el potencial de almacenamiento tienen el potencial de fomentar un mayor uso del recurso, siempre que existan soluciones técnicas competitivas.

1. Introduction

In the early 1980s the Swedish Energy Agency (SWEA) promoted actions where fossil fuels for heating purposes could be substituted by other sources of energy. This aroused interest in investigating the potential of geothermal energy as a contributor of heat to the district heating systems. One potential geothermal reservoir was the Upper Cretaceous Lund Sandstone in southwest Skåne, the southernmost province of Sweden. In 1981 the department of Engineering Geology, Lund Energy (today Kraftringen AB) and the General Swedish Electrical Company (ASEA STAL AB) presented a concept to utilise this reservoir. A full-scale system was built and put into production in 1984 [1,2]. Despite, relatively low initial formation temperatures (about 21 °C), it was economically feasible to utilise the reservoir for geothermal heat to the city of Lund. This was largely related to a significant gross thickness of several hundred metres, a high net sand share, high porosity, and permeability. The built capacity corresponded initially to about 40% of the district heat demand in Lund. However, lower temperatures and flow capacities have resulted in a gradually decreasing share. All this is as expected in the life-cycle models, based on production capacities, distances between production and injection wells, and the lifetime for the well components [3,4]. Overall, the lifespan of the system is much better than expected. The system is still operating – although with reduced capacity – after 37 years and demonstrates a successful use of this geothermal resource, especially regarding the operational experience and environmental benefits. Along with other examples of long-time utilisation [5], this shows that sustainable geothermal production is viable.

Although the Lund Sandstone is found beneath several urban areas in southwest Skåne, its geothermal value is largely unknown. This is partly due to the fact that little has been published that shows its geothermal value, including distribution and volume of the reservoir, and available amount of heat. Early on publications primarily presented site-specific operational experiences from the Lund geothermal plant [1–4,6] and not the entire reservoir. Aside from a brief description in the European Geothermal Atlas in 2002 [7], until this study there had not been any regional GIS data of the reservoir showing the depths and the gross volume for the calcu-

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lation of the available heat. The GIS data, together with a comprehensive compilation of previously unpublished well data on the reservoir properties [8], has made it possible to assess the resource from a regional perspective for the first time. In addition, an increasing number of heat-in-place (HIP) calculations during the last decades on various geothermal reservoirs and scales [9–12] provide valuable references on the methodology as well as on heat-in-place estimates in a European perspective.

The Lund Sandstone has lately also been assessed concerning its energy storage potential [13,14], which further highlights its value. As the European Commission [15] states, decarbonising the energy demand and increasing the utilisation of renewable resources is of paramount importance. This largely aims to increase the capacity to store energy when other renewable resources are integrated in the energy grids. This is also emphasised in the Geological Service for Europe (GSEU) project [17] that will directly support the vision of the European Green Deal [18], including thematic work on resource assessments of pan-European geothermal energy and underground storage. There is a potential to increase the share of geothermal energy but that the potential needs to be better promoted and recognised. In this context an assessment of the available heat in the Lund Sandstone provides valuable information to a region in southernmost Sweden with about 300,000 inhabitants, mainly living in five urban areas with district heating systems that facilitate the use of geothermal heat. Hence, this study aims to increase awareness of the resource by demonstrating the operational experiences, reservoir characteristics, distribution, and calculations of the HIP (GJ/m^2) and heat storage potential (HSP, GJ/m^2) for the Lund Sandstone.

2. Study area

2.1 Geological setting and data

The Lund Sandstone is found in the easternmost margins of the Mesozoic Danish Basin, adjacent to the bounding Romeleåsen Fault Zone to the NE (***Figures 1, 2***). The distribution is based on wells and seismic data from surveys by the Swedish Oil Prospecting CO (OPAB) in the early 1970s, Swedegas AB in the 1980s and by Lund Energy (today Kraftringen AB) and the department of Engineering Geology in 2001 and 2008 [8]. The reservoir properties are evaluated from wireline logs, core analyses and hydraulic data from 20 exploration wells [8].

The several hundred-metre-thick reservoir is found within a c. 1,500 m thick Upper Cretaceous–Paleogene limestone-dominated succession (***Figure 1***) and consists of deltaic sandstone, formed during the late Campanian by extensive erosion and deposition, related to Alpine compression tectonics and uplift of the Sorgenfrei-Tornquist Zone [18,19].

The sandstone is defined as the Lund Sandstone Member in the Upper Cretaceous–Paleogene Höllviken Formation [20]. The gross thickness is up to c. 700 m in the northeast, while gradually thinning to the southwest and gradually becoming finer grained (***Figure 2a***). In the study area, the Lund Sandstone is found between 350 and c. 1,100 m depth (***Figures 2b and 3***). The net sand share is based

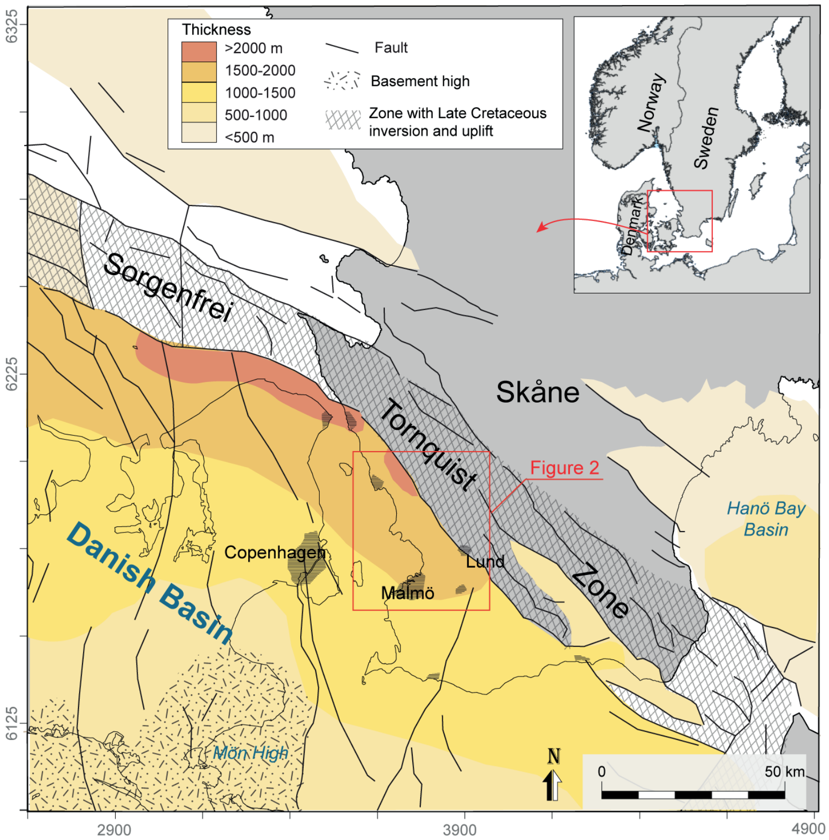

Figure 1: Location map with the main structural elements and gross thickness of the Upper Cretaceous, including the Lund Sandstone. Coordinates are given in the Swedish National Grid SWEREF99.

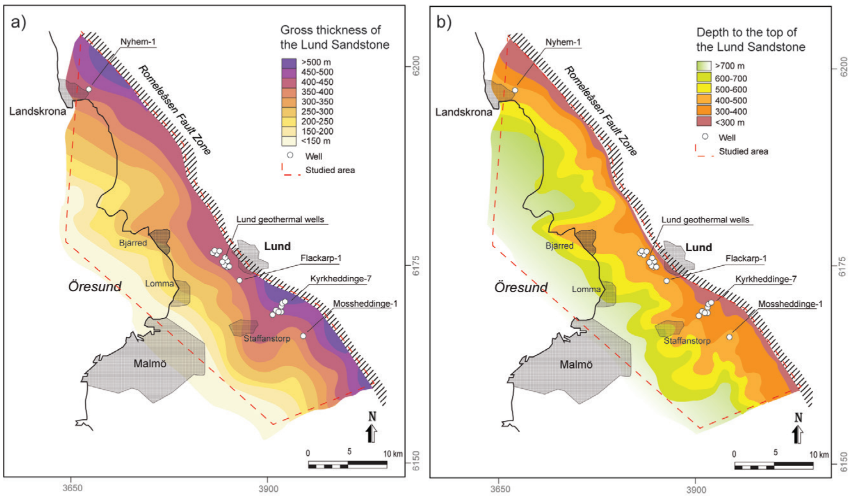

Figure 2: a) map showing the gross thickness of the Lund Sandstone, b) depth contour map of the top of the Lund sandstone.

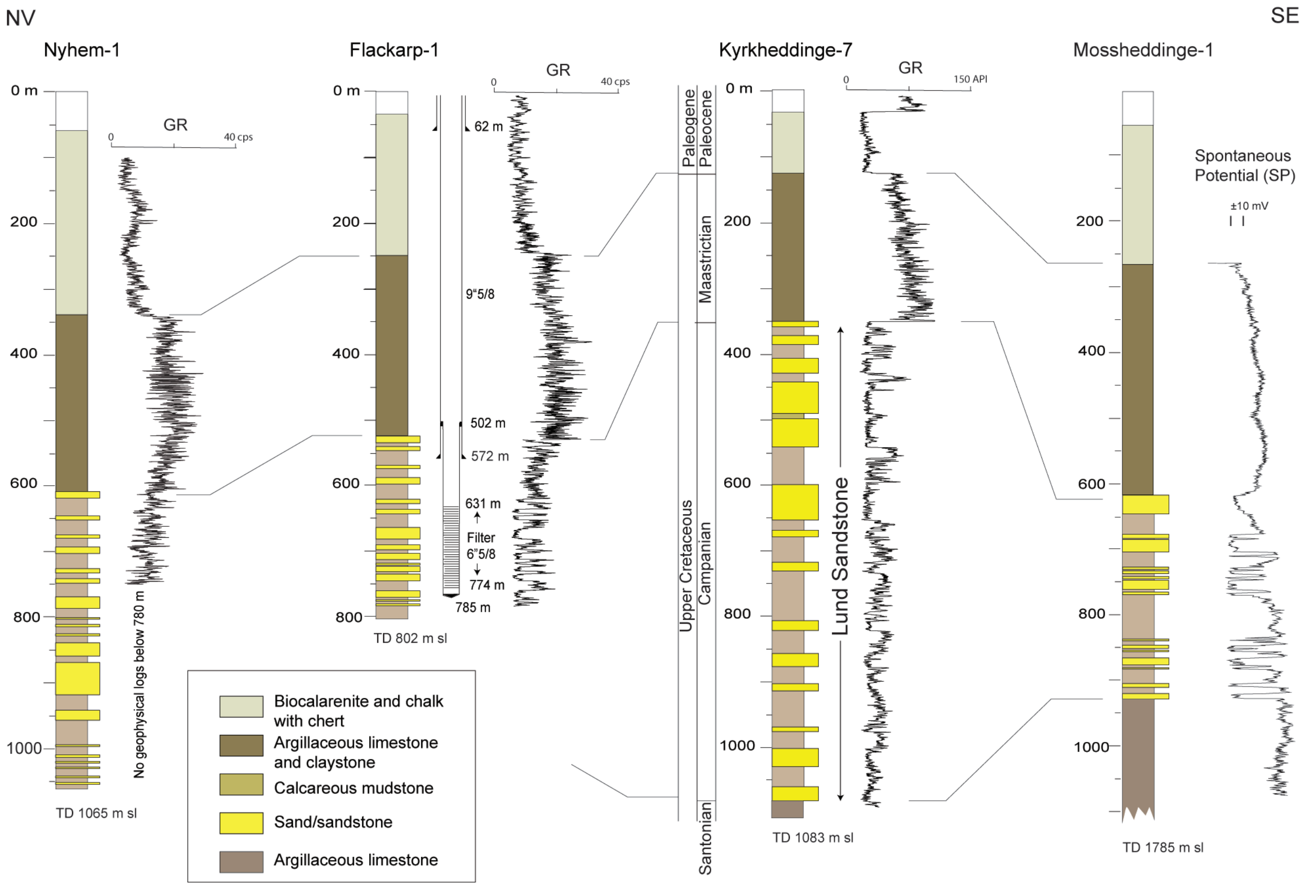

Figure 3: Examples of well log profiles within the studied area from the northwest to the southeast. The well locations are shown in Figure 2. The well design of producing interval in the Lund geothermal field is exemplified by the Flackarp-1 well.

on a porosity cut-off value of 15% using data from Sonic and Neutron logs. The net sand share varies between 50 and 80% of the gross thickness in the northeast parts and c. 20–30% in the southwest parts of the study area.

The formation temperatures commonly range between 17 °C and 35 °C for reservoir depths between 350 and 1,100 m. The reservoir pressure is equivalent to the hydrostatic pressure.

The reservoir contains commonly up to 50 m thick highly porous and permeable sandstone units separated by argillaceous and arenaceous limestone and calcareous claystone. Core analyses on sandstone beds show a porosity between 20 and 32% and a permeability of up to about 6 Darcy, but commonly 1.1–2.7 Darcy [8]. Hydraulic tests give a hydraulic conductivity of about $6 \cdot 10^{-5}$ m/s and a transmissivity of $3–5 \cdot 10^{-3}$ m^2/s [1]. The geothermal fluid contains up to 2.5 dm^3 gas/100 dm^3 of formation water and is dominated by nitrogen, a few percent methane and helium. The geothermal water from the production wells has a pH of 6.9, density of 1,030 kg/m^3, chloride concentration of 2.6% and an iron content of 28 mg/l [3].

2.2 The geothermal plant in Lund

The Lund geothermal plant includes four production and four (initially five) injection wells to depths between 654 and 768 metres below sea level. In addition, there are two observation wells including Flackarp-1 (***Figure 3***). The wells are completed with a 20" (508 mm) conductor casing to 25–75 m depth, sealing off the Quaternary deposits and the freshwater aquifers. The next section, drilled with a 17 ½" (445 mm) bit, is completed with a 13 3/8" (340 mm) casing cemented up to the surface. The reservoir was drilled with a 12 ¼" (311 mm) bit using a KCl polymer-based mud. The selected production interval was reamed to 15" (381 mm) before being completed with gravel pack, 7 5/8" (194 mm) (OD) stainless blanks and 6 5/8" (168 mm) (OD) wire wrapped screens. The uniformity coefficient C_u-value (d_{60}/d_{10}) of the formation sand is below 2.5 and therefore a gravel pack completion was chosen. The screen lengths vary between 61 and 147 m. The longer ones are in the injection wells, allowing a decrease of the injection pressure. The slot width is either 0.5 or 0.8 mm and the grain sizes of the gravel pack are either 0.7–1.2 mm or 1.0–1.7 mm.

A submersible pump (OD 290 mm) with a capacity of 120 l/s is mounted at the bottom of a production pipe (OD 200 mm) at c. 70 meters depth in the production wells. The distances between the production and injection wells vary between 1,310 and 2,350 m.

The geothermal plant is built on two ASEA STAL heat pumps with a maximum heat output of 21 MW and 27 MW. Two step-turbo compressors supporting the refrigerant have an inlet pressure of 16 bar, intermediate pressure of 25 bar and output pressure, after the compressor, of 40 bar. Each compressor is driven by an electrical motor rated to 6.5 and 9 MW respectively. The heat pumps initially contained 15- and 20-ton refrigerant R500, which was in 1995 substituted by R134a. The coefficient of performance is on average 3.5 [3].

Wells and heat pump plant are connected by a 4.2 km long system of fibreglass reinforced plastic tubes (600 mm OD) that resist a temperature of 35 °C and a pressure of 16 bar. The pipes are placed beneath ground at a depth of c. 1.5 m on a

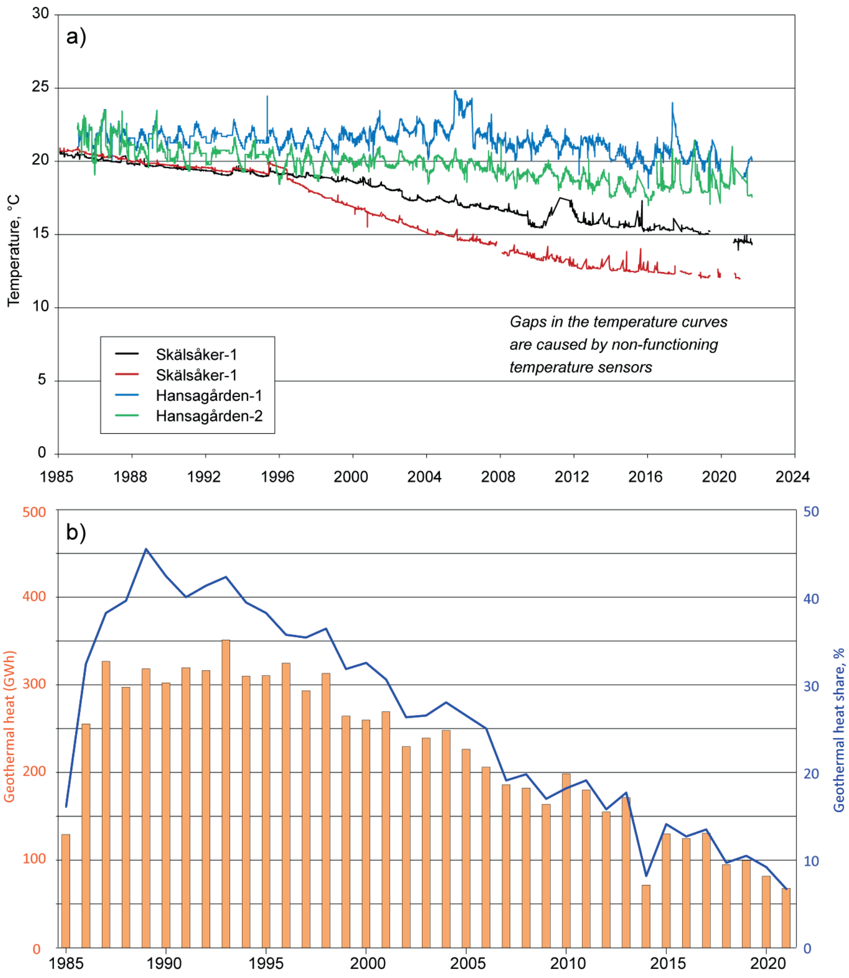

Figure 4: a) graphs showing the temperature decrease with time in the four production wells. Note that the temperature decrease is greatest in Skälsåker-1 and -2, which are the two wells located closest (c. 1,310 m) to the injection wells, b) composite graph illustrating the amount of geothermal energy coming from the geothermal plant in Lund and its share of the total heat demand in the Lund district heating system.

bed of quartz sand.

The geothermal plant has from the start operated 6,000–8,500 hours/year with an average flow of around 1,650 m^3/h. However, the average production temperature has dropped from c. 21 °C to c. 19 °C due to a temperature decrease of 4–8 °C in two of the production wells (***Figure 4a***). The temperature drop is caused by relatively colder formation water moving from the injection wells towards the nearest production wells. The injection temperature varies between 4 and 7 °C. The decreasing production temperature has resulted in a declining amount of heat to the district heating, from 300–350 GWh/year to 100 GWh/year (***Figure 4b***). Before the drop in production temperature it contributed up to 45% of the district heating in the city of Lund. Besides the temperature decrease, the gradually decreasing share is also caused by increasing competition from other heat resources to the district heating, as well as an increasing number of stops due to maintenance of the aging system.

A recurring problem is that the injection pressure gradually increases during operation. This has been mitigated by regular airlifting operations to reactivate and stimulate the gravel pack. Despite the airlifting, the increase of the injection pressure enforced a coiled-tubing hydro jetting operation in 2012–2013 to remove fines, scaling and clogging. This successful operation resulted in regained injection flow rates in all wells. However, the most troublesome concern today is the integrity of the old wells. Well inspections with wire-line logging tools, such as Video, Caliper, flow meter and temperature, have been performed on several occasions. One injection well has been abandoned due to a collapsed casing. It is noteworthy that the casing intervals in front of the pump locations have had to be repaired due to abrasion.

Furthermore, the change in refrigerant in 1994 and 1995 resulted in a slight decrease in output effect of the heat pumps. Within the coming years, the currently used R134a refrigerant must be replaced, due to new regulations. One alternative is to replace the R134a with a R-1234ze refrigerant. However, this will lead to an additional 20% reduction. This is still a critical issue regarding the future operation of the Lund geothermal system. Although the Lund geothermal system has proven to operate far better than initial expectations, it is still uncertain whether any new wells will be drilled, primarily because of the competition from other energy sources, such as heat from incineration of waste and biomass.

3. Methodology

The most widely used method for geothermal resource assessments is calculating the maximum theoretically extractable heat in an aquifer (HIP) [21]. We have here applied a method initially developed by the United States Geological Survey [22] which is suited for low temperature aquifers like the Lund Sandstone. It also used for the assessments given in the European Geothermal Atlas [23] and concluded to be the most useful tool for evaluating geothermal reservoirs at an early stage of development [22]. This method, also known as the volumetric method, gives a simplistic estimate based on relatively few input parameters [22,24]. Basically, the HIP is calculated as the theoretical amount of thermal energy stored in a volume of a reservoir rock, under homogeneous conditions regarding porosity, density, heat capacity and temperature gradients.

The first step in our study was to define the volume by constructing depth maps for the top (***Figure 2b***) and base of the Lund Sandstone. From this the gross thickness (***Figure 2a***) and volume of the reservoir is given. The temperature to the top of the reservoir is calculated from a uniform gradient of 2.5 °C/100 m and a mean surface temperature of 8 °C. The net sand share is assessed to decrease stepwise from 60% where the gross thickness is >500 m to 20% in the outer parts of the studied area, where the gross thickness is <150 m. Similarly, a decrease in porosity from 25% to 15% was assessed in the calculations from northeast to southwest.

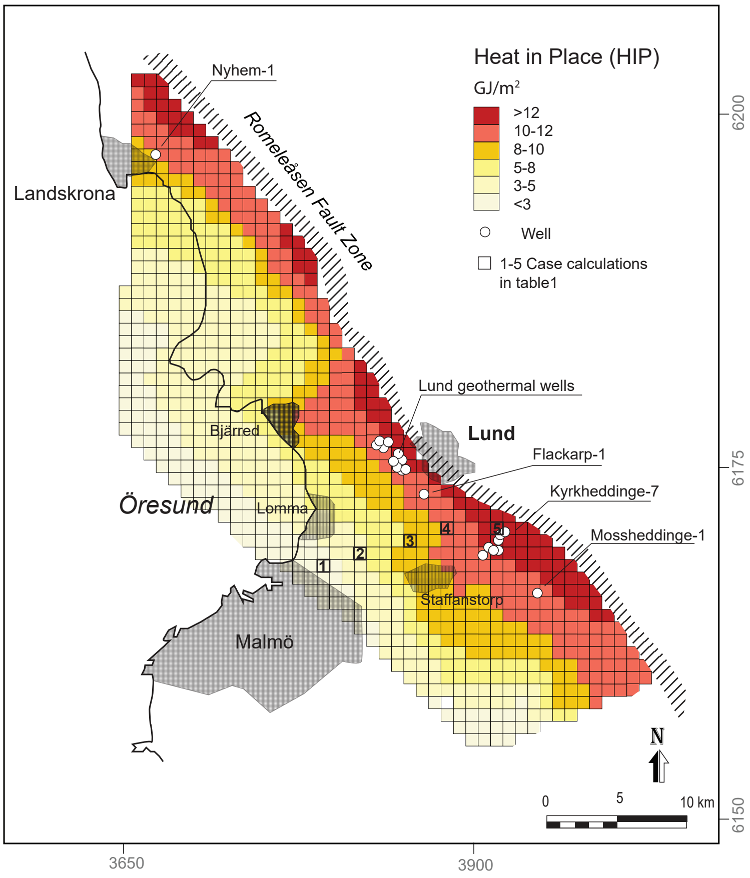

Figure 5: Schematic map of the estimated heat-in-place (HIP, GJ/m²) reserves in the Lund Sandstone.

Table 1: Input parameters for the different case calculations of heat-in-place (HIP) and heat storage potential (HSP). The cases exemplify the range of energy present at various locations where depth, gross thickness, net sand, porosity, and temperature of the Lund Sandstone reservoir differs. The locations are shown in Figure 5.

Parameter			Case 1	Case 2	Case 3	Case 4	Case 5
Minimum depth	d_{min}	m	650	500	450	400	350
Maximum depth	d_{max}	m	800	850	850	900	1,050
Gross thickness	h_g	m	150	350	400	500	700
Net sand	h_n	m	30	100	200	300	400
Surface area	A	m²	1.0E+06	1.0E+06	1.0E+06	1.0E+06	1.0E+06
Effective porosity	Ø	%	0.15	0.20	0.20	0.25	0.25
Effective reservoir volume	V_A	m³	3.0E+07	1.0E+08	2.0E+08	3.0E+08	4.0E+08
Top reservoir temperature	T_R	°C	24	21	19	18	17
Injection temperature	T_{inj}	°C	4	4	4	4	4
Density water	ρ_w	kg/m³	1,030	1,030	1,030	1,030	1,030
Density matrix	ρ_s	kg/m³	2,620	2,620	2,620	2,620	2,600
Specific heat capacity water	C_w	J/kg°C	4,180	4,180	4,180	4,180	4,180
Specific heat capacity solids	C_s	J/kg°C	800	800	800	800	800
Volumetric heat capacity	C_A	MJ/m³°C	2.43	2.54	2.54	2.65	2.65
Heat in place	HIP	GJ/m²	1.5	4.2	7.7	11.1	13.4

Most of the work was performed by using the ArcGIS software.

$$C_A = Ø \times \rho_w \times C_w + (1 - Ø)\rho_s \times C_s \qquad (1)$$

$$HIP = V_A \times C_A \times (T_R - T_{inj}) \qquad (2)$$

$$HSP = V_A \times C_A \times (T_{inj} - T_R)F_r \times F_p \qquad (3)$$

Our calculations using the volumetric method, defined by equations (1) and (2), are mainly based on parameters and values exemplified in ***Table 1***. The values come from well data in the Lund and Kyrkheddinge area (***Figure 2a, b*** and ***Figure 5***) [8]. The specific heat capacity of the formation water is set to 4,180 J/kg°C, corresponding to fresh water, for reasons of simplification. In reality, a slightly lower but unknown value could be expected due to a slightly saline formation water. The specific heat capacity of the rock matrix (C_s) is set to 800 J/kg°C [25].

In addition, following the workflow presented by [10], the heat storage potential (HSP) is calculated using equation (3). The effective storage volume is also considered to be half of the total, which is further reduced by compression packing (F_p) and recovery (F_r) factors [26–28]. In this case we use F_p=0.8 and F_r=0.7, like the models used for the North German Basin study by [17].

The actual amount of heat that can be extracted from the reservoir depends on a recovery factor. This factor is for a production-reinjection doublet defined by Lavigne to be 0.33 [29]. This definition is also widely used in other assessments [9–11]. The fraction (R_0) of extractable amount of heat also depends on a reference surface temperature (T_0), production temperature (T) and the reinjection temperature (T_{inj}) according to equation (4).

$$R_0 = 0.33 \times (T - T_{inj}) / (T - T_0) \qquad (4)$$

4. Results and discussion

Using equation (1) gives a volumetric heat capacity (C_A) of 2.43–2.65 MJ/m³°C, which fall within the range of typical sandstone values [30]. The HIP, calculated for one-square-kilometre large blocks, using equation (2), ranges between 1.5 and 13.4 GJ/m². Sample calculations are shown for five locations (cases 1–5) with various reservoir properties related to increasing distance from the bounding Romeleåsen Fault Zone, with corresponding step-wise reduced reservoir properties such as gross thickness, net sand share and porosity (***Table 1***, ***Figure 5***).

The main part of the studied area, i.e., where the top of the reservoir is deeper than 400 m, the net sand >100 m and the temperature >20 °C, have HIP values above 8 GJ/m^2. This is significantly higher than for a Lower Cretaceous reservoir in the Lisbon region (3.8 GJ/m^2) [12] and for Mesozoic reservoirs in the North German Basin [10] but in the same range as the geothermal reservoirs in the Paris Basin (7.0 GJ/m^2) [31]. HIP values ranging between 3 and 10 GJ/m^2 are also mentioned for Triassic and Jurassic reservoirs with temperatures of 45–80 °C in the Danish Basin in Denmark [9]. Considering 5–8 GJ/m^2 for the main part of our studied area, this will add up to a conservative estimated HIP reserve of 1,000–1,600 PJ. Since the injection temperature in the Lund case is similar or commonly lower than the reference surface temperature, this means that the extractable heat will be about 1/3 of the calculated HIP values.

Considering a rough estimate for the heat consumption in the district heating systems of 4 PJ/year for the urban areas of Landskrona, Lund, Staffanstorp, Bjärred and Lomma [32], we find that the reserves could provide geothermal heat to these systems for several hundred years. We should note that the HIP calculations have not considered the replenishment of heat by conduction from layers above and below. Even if this factor has greater impact on deeper and thinner reservoirs and moderate production rates, it should be further evaluated for the Lund Sandstone.

The HSP is in our case based on a 20 m thick homogeneous sandstone interval, with an effective porosity of 25% and a formation temperature of 20 °C. The heat is stored at an injection temperature of 90 °C. This gives a HSP value of 1.0 GJ/m^2 in our case. This is slightly higher than the high-end values for the Keuper reservoirs in the North German Basin [10]. Thus, considering the favourable depth, which brings down the cost of drilling, and good reservoir properties, the aquifer thermal energy storage (ATES) potential in the Lund Sandstone is considerable.

5. Conclusions

The Lund Sandstone is here assessed as a substantial geothermal resource in SW Skåne, southernmost Sweden. Our estimates give that the heat in place is commonly around 8 GJ/m^2 within an area of 200 km^2. This corresponds to several hundred years of consumption in the local district heating systems, supporting five urban areas and about 300,000 inhabitants.

So far, the resource has only been exploited in the city of Lund, where since 1985 it has provided several hundred GWh heat yearly to the district heating system. Beyond expectations, the geothermal plant is still operating, but with a decreasing capacity due to gradually less well functioning wells and increasing temperature interference. Despite over 37 years of successful operation and environmental benefits, this resource is largely an untapped and poorly recognised heat and storage resource in the region. Our calculations show a high heat storage capacity of 1.0 GJ/m^2, a relatively shallow target depth, high porosity and permeability, homogeneity, and a formation of temperature of around 20 °C, which is especially advantageous for storage.

Unfortunately, further exploration has been essentially neglected because of a lack of awareness and due to competition from and pricing of other energy sources. However, it is hoped that highlighting the magnitude of the heat reserve and the storage potential will foster further exploration and use of the resource, provided there are feasible competitive technical solutions for its future utilisation.

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Geothermal resources for energy transition: A review of research undertaken for remote northern Canadian communities

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The sustainable development of Canada's north is a growing challenge. Nearly 134,000 people, mostly Indigenous, live typically in a diesel-dependent dynamic, and thus initiatives to deploy clean technologies for heat and electricity are ongoing. Research is underway in the Yukon, Northwest Territories and Nunavut to assess geothermal resources of target communities while techno-economic feasibility of geothermal technologies is being evaluated in Nunavik (Quebec). Results suggest that geothermal technologies can provide important carbon reductions and are economically attractive. While shallow systems can be deployed in a short-term period, deep systems are a long-term objective that may provide sufficient energy to meet communities' heavy heating needs.

Le développement durable du nord du Canada est un défi croissant. Près de 134000 personnes, la plupart autochtones, dépendent fortement du diesel. Ainsi, des initiatives visant à déployer des technologies propres pour le chauffage et l'électricité sont en cours. Des travaux de recherche sont réalisés au Yukon, Territoires du Nord-Ouest et Nunavut pour évaluer les ressources géothermiques de communautés cibles alors que la faisabilité technico-économique des technologies géothermiques est étudiée au Nunavik (Québec). Les résultats suggèrent que les technologies géothermiques peuvent permettre d'importantes réductions de carbone et sont économiquement intéressantes. Alors que les systèmes superficiels peuvent être déployés à court terme, les systèmes profonds sont un objectif à long terme qui pourrait fournir suffisamment d'énergie pour répondre aux besoins de chauffage des communautés.

La sostenibilidad del norte de Canadá es un desafío cada vez mayor. Casi 134 000 personas, en su mayoría indígenas, dependen en gran medida del diésel. Por eso, se están llevando a cabo iniciativas para desplegar tecnologías limpias para la calefacción y la electricidad. Yukón, Territorios del Noroeste y Nunavut están haciendo investigaciones para evaluar los recursos geotérmicos de comunidades seleccionadas, y en Nunavik (Quebec) se está evaluando la viabilidad tecno económica de las tecnologías geotérmicas. Los resultados sugieren que las tecnologías geotérmicas pueden proporcionar importantes reducciones de carbono y son económicamente atractivas. Mientras que los sistemas superficiales pueden desplegarse a corto plazo, los sistemas profundos son un objetivo a largo plazo para satisfacer las necesidades de calefacción de las comunidades.

1. Introduction

Canada is a vast, cold and energy-intensive country that is making strong commitments to reduce carbon emissions and reach a climate neutral society [1]. While about 60% of Canada's power comes from non-emitting sources [2], the situation in the north is different [3]. Remote northern communities in Canada are geographically distant and there are only a few areas with a regional electricity grid, some supported by hydropower (***Figure 1***). The remainder, comprising just over 100 communities – mostly Indigenous, with about 134,000 inhabitants – often rely on diesel for heat and power. Other sites, such as mines and military bases, likewise mostly rely on diesel (***Figure 1***).

Given Canada's commitment to reduce its greenhouse gas emissions, issues associated with diesel fuel used in the north (e.g., spills and soil/groundwater contamination, supply chain disruptions) and the desire to support economic development in this region, it is imperative to investigate alternative sources to find those that can provide clean, local, stable, reliable, and cost-effective power and heat.

Geothermal resources can play a significant role in the energy transition of diesel-based communities as a standalone solution or integrated with other renewables (e.g., [4]). In Canada, energy produced from deep and shallow geothermal systems is receiving growing attention and Tu Deh-Kah Geothermal (***https://tudehkah.com/***) and Fuel for Reconciliation (***https://www.kitselasgeo.ca/***) are two inspiring examples of community geothermal projects underway. Beyond electricity and space heating, geothermal resources can supply the heat needed for greenhouse applications. Food security is an additional issue in northern Canada and geothermal resources can provide a baseload source of local energy to support food production, as highlighted by a proof-of-concept study undertaken in Resolute Bay (Nunavut; [5]).

Despite the potential valuable contribution that geothermal energy can add to the energy transition of remote northern

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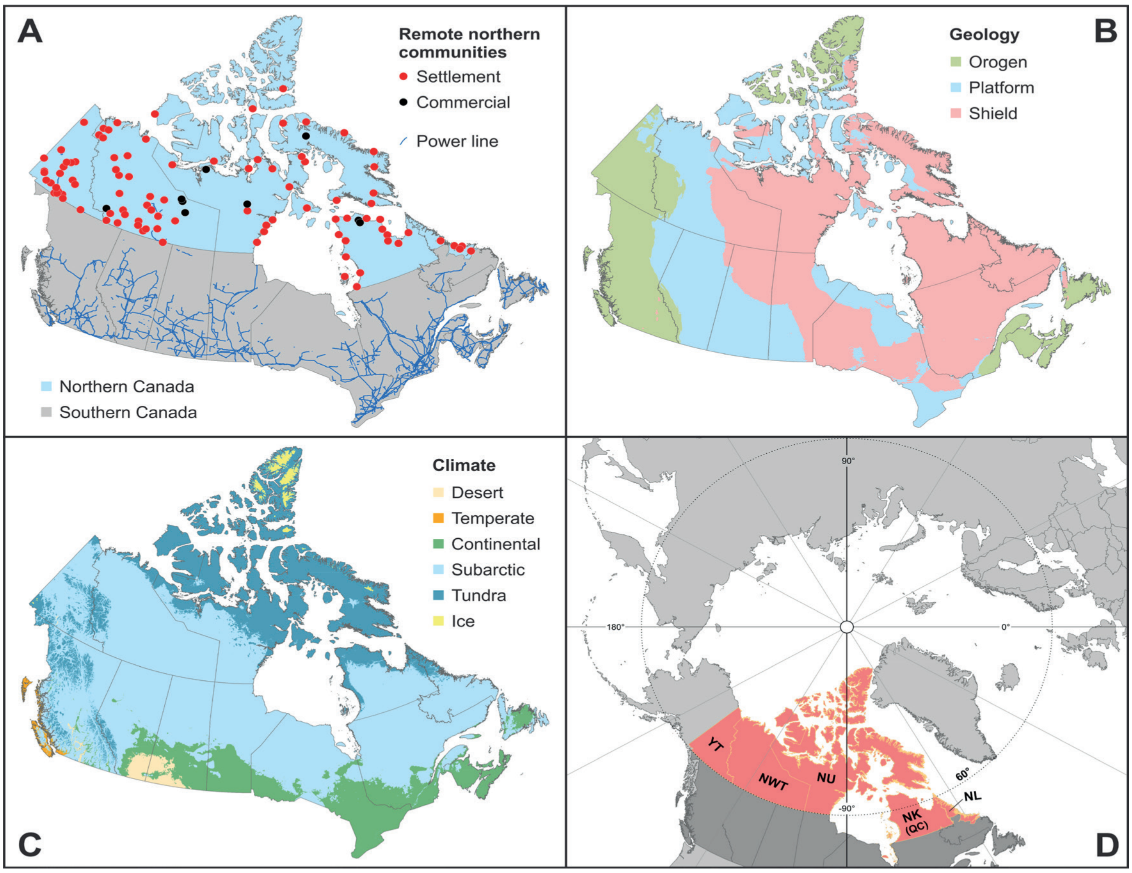

Figure 1: (A) Location of remote northern communities in Canada; (B) main geological regions; (C) climate zones; and (D) map of the studied area centered on the Arctic. YT – Yukon Territory, NWT – Northwest Territories, NU – Nunavut, NK – Nunavik, QC – Quebec and NL – Newfoundland and Labrador (Nunatsiavut).

communities [6-8], there are still important data gaps in many areas of northern Canada [9] (***Figure 2***). Existing data, mainly from oil and gas exploration, assess only about 40% of Canada's landmass (***Figure 2***) and most of the previous work in northern Canada has focused on sedimentary basins in the Northwest Territories, northern Yukon and Canadian High Arctic [8] due to the existing wells. Currently, many territorial initiatives supported by various levels of government are underway to intensify the data collection and find viable targets. The ongoing work includes both expanding existing knowledge in the sedimentary basins and addressing the almost complete absence of geothermal-relevant data in the rest of Canada's north.

The purpose of this paper is to summarise geothermal research being undertaken for the remote northern communities of Canada (***Figure 1***). In this review, the goal was to cover most regions that are not connected to major power grids, where the climate is cold and the heating needs are generally more than 8,000 heating degree days below 18 °C (HDD$_{18}$[1]) [10], and where active geothermal projects are being undertaken.

2. Deep geothermal potential of northern Canada

2.1. Yukon Territory

Yukon has several potential hydrothermal plays including fault controlled, radiogenic intrusive, volcanic, and sedimentary basin types (***Figure 2A***). A geothermal feasibility study revealed potential areas of interest (***Figure 3A***), and suggested resources consisting of more than 1.7 GW potential at <5 km, and approximately 100 MW potential at <2 km [11]. However, heat flow data is sparse (***Figure 2B***) and detailed assessment is necessary to fully understand Yukon's geothermal potential. A well drilled near Takhini hot springs, close to Whitehorse, revealed a variable geothermal gradient with depth, suggesting fracture-controlled groundwater influx, and further work is needed to understand the hydrothermal system (***Figure 3B***; [12-14]). Another well drilled in the Tintina Trench near Ross River revealed greater geothermal gradient than predicted for the area (30.6 °C/km vs 25 °C/km; ***Figure 3C***; [12,14]). Studies are underway to assess the geothermal potential in SW Yukon where deep water wells in the communities of Haines Junction and Burwash Landing provide water at 16-17 °C, and the Jarvis warm springs emerges at 18 °C [15]. Additional regional studies show there may be thermal potential related to Cretaceous intrusive rocks and volcanic belts [16].

2.2. Northwest Territories

The Northwest Territories (NWT) are characterised by three main geothermal plays: the Canadian Shield petrothermal system, Paleozoic and Mesozoic sedimentary basins hosting high temperature geothermal resources in deep aquifers with known thermal anomalies, and the Mackenzie Mountains with numerous thermal

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[1] Heating Degree Days (HDD) are equal to the number of degrees Celsius a given day's mean temperature is below 18 °C [10]. The number of degree days is a measure of the heating needs based on difference between the base temperature and the outdoor temperature over the year.

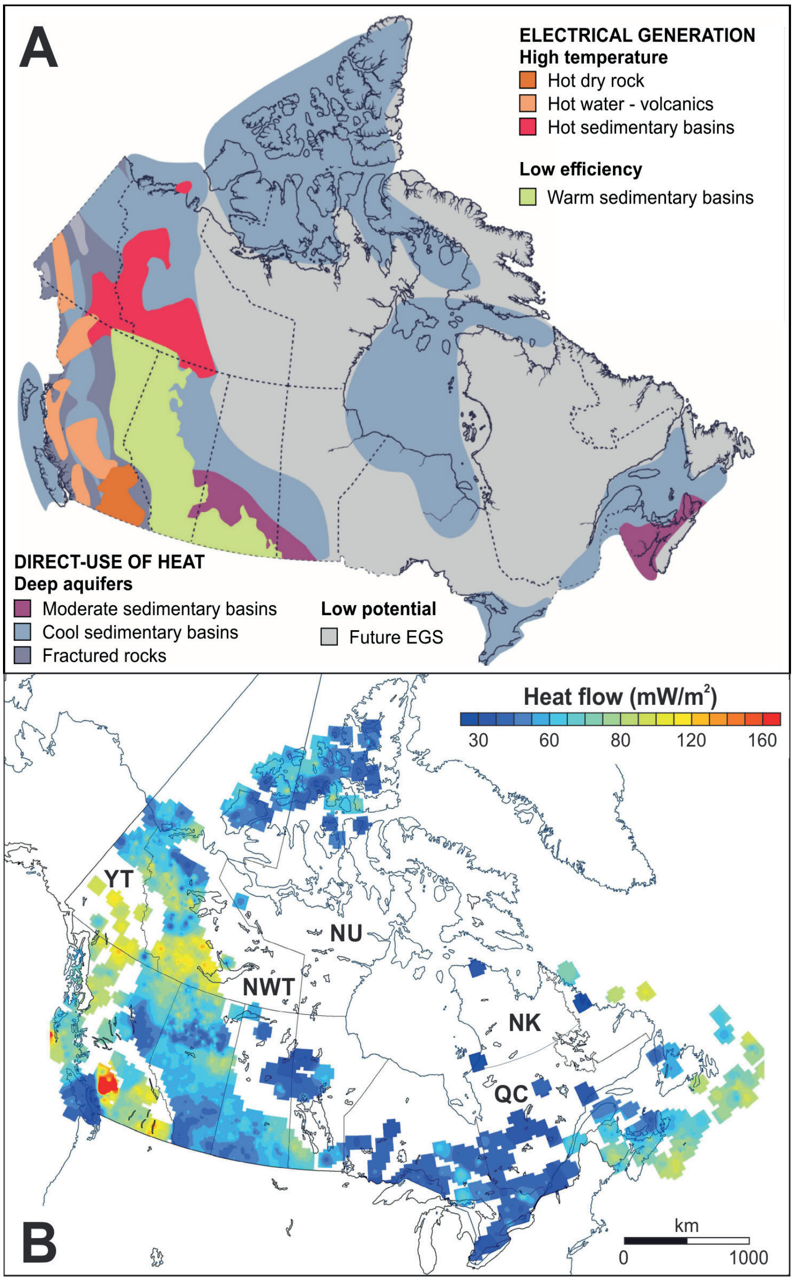

Figure 2: (A) Distribution of geothermal potential in Canada based on end-use (after [9]); (B) Heat flow map of Canada (after [9]). YU – Yukon Territory, NT – Northwest Territories, NU – Nunavut, NK – Nunavik, QC – Quebec.

springs and high temperature intrusives (***Figure 4***; [17]). The Canadian Shield is characterised by a low heat flow and geothermal gradient (~ 17.6 °C/km) that limit the resource largely to heat pump systems, abandoned mines, and potentially enhanced geothermal systems (EGS). Deep conventional geothermal technologies can be foreseen in sedimentary basins to generate power and for direct use of heat [18]. In the sedimentary basins of southern NWT, the geothermal gradient can be up to 50 °C/km and heat flux as high as 90 mW/m^2 [7,18,19,20].

Research is underway in the Fort Liard area and in the South Slave region enclosing Hay River, Enterprise, and Fort Providence to assess the geothermal potential of these communities (***Figure 4***).

2.3. Nunavut

All communities in Nunavut rely on diesel. For this reason, Qulliq Energy Corporation, the company generating and distributing power in Nunavut, is interested in evaluating the territorial geothermal potential and is assessing some target communities for future geothermal development. Nunavut has two major geothermal plays: sedimentary basin geothermal resources and the Canadian Shield, where EGS or deep borehole heat exchangers may be necessary to exploit the resource [22,23]. The average heat flux in Nunavut is about 40-60 mW/m^2, but values as high as 70 mW/m^2 can be found in the Canadian Arctic Islands (***Figure 2B***; [23]). The technical power generation potential was estimated to vary between 59 MWe and 64 GWe in the Canadian Shield and between 662 MWe and 96 GWe in the sedimentary basins in the Arctic Islands [23].

A geothermal feasibility study was carried out in 2018 [23] and concluded that additional data collection with drilling in target communities (e.g., Resolute Bay, Baker Lake) is necessary to properly define the resource potential (***Figure 5***; [23]). It is also suggested that, given the remoteness and great distance of the communities from each other, the lack of infrastructure to support energy transfer, and the resource temperature, geothermal developments should occur in or near the communities [23].

2.4. Nunavik (Northern Quebec)

Nunavik is home to 14 Inuit communities and, as in many parts of northern Canada, the geothermal data availability is limited. Thus, the surface heat flux and subsurface temperature maps produced for this region are based on extrapolation of sparse data and are therefore uncertain (***Figure 6A-B***).

Only four deep wells (>300 m) exist in Nunavik indicating a geothermal gradient of 9–17 °C/km and a heat flux of 26–38 mW/m^2 (***Figure 6***; [24-28]). However, a recent well drilled in Kuujjuaq (~240 m) suggests greater local geothermal gradient and heat flux, with a most probable value of 21 °C/km and 57 mW/m^2, respectively [29]. Such differences illustrate data gap challenges that must be faced when evaluating the geothermal potential. This variability can indeed make a significant difference when assessing the techno-economic viability of deep geothermal technologies, highlighting the need for intensive data acquisition completed at the community rather than the regional level. Nevertheless, all of the studies undertaken [24,25,30-35] agree that ground-coupled heat pump (GCHP) systems can be readily deployed for energy savings of buildings in subarctic communities while research is underway to fully

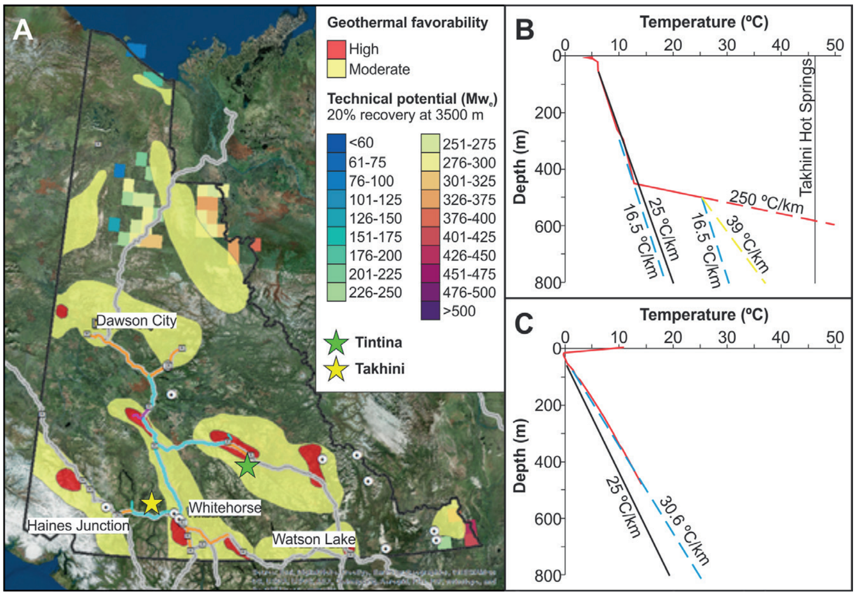

Figure 3: (A) Primary geothermal exploration areas in Yukon Territory (after [11]); (B) stabilised downhole temperature data for the Takhini well, interpretative geothermal gradients and the surface water temperature at Takhini Hot Springs (after [12]), (C) stabilised downhole temperature data for the Tintina well and interpreted geothermal gradient (after [12]). The reader is referred to Figure 1 for geographical location. It is important to highlight that in (B) there is only one data point that shows an anomalous temperature value and therefore the gradient hypotheses shown are only rough approximations and may be overestimated.

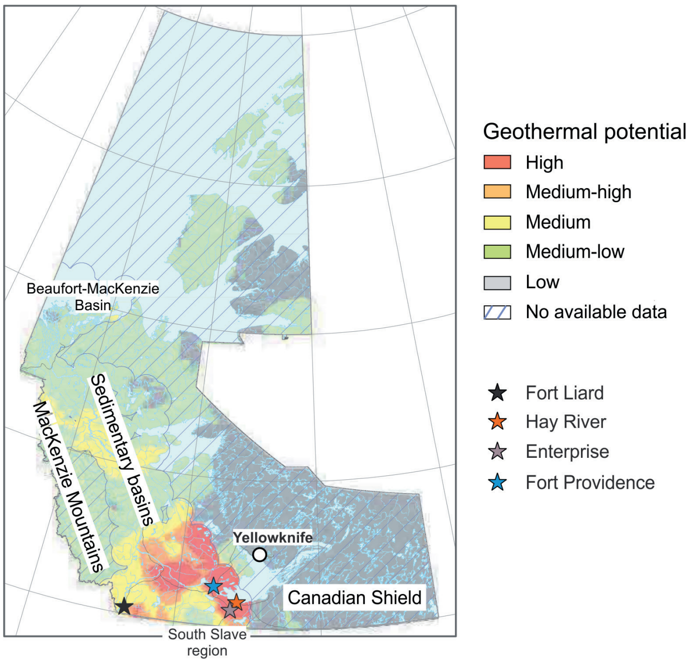

Figure 4: Northwest Territories geothermal favourability map (after [21]). The reader is referred to Figure 1 for geographical location.

assess the communities' deep geothermal potential and the technological feasibility and economic viability of related technologies. Deep geothermal should be seen as long-term goal that, if feasible and cost competitive, could meet the whole heating needs and perhaps part of the electricity demand of each community.

3. Geothermal technologies for northern communities

3.1. Ground-coupled heat pumps (GCHP)

GCHPs are a well-established technology in southern Canada and could become one of the alternatives to heat buildings in remote subarctic communities. Simulations of GCHP operation undertaken for a typical commercial building in Kuujjuaq (***Figure 6***) showed that energy savings are of the order of 55 to 76% [30] and a 50-year life-cycle cost analysis suggests that shallow geothermal energy with state-of-the-art heat pumps is a financially interesting option [31].

Furthermore, shallow geothermal mapping in Kuujjuaq (***Figure 6***; [31]) and Whapmagoostui-Kuujjuarapik (***Figure 6***; [32]) suggest that a 100 m deep borehole heat exchanger may be able to provide, on average, 5.8 and 12 MWh/year, respectively. Additionally, a compression heat pump with a proportion of its electricity consumption derived from solar photovoltaic panels seems an economical and eco-friendly heating solution for both residential dwellings (***Table 1***; [31]) and commercial buildings [33]. However, these studies showed that the source of the electricity originating from a diesel plant limits the economic and environmental benefits of heat pumps.

Horizontal closed-loop GCHP systems installed in the active ground layer above the permafrost can also be a viable solution for remote northern communities. Belzile et al. [34] concluded that an air-source absorption heat pump in Kangiqsualujjuaq (***Figure 6***) may offset 17.4% of diesel consumption while a ground-source absorption heat pump may offset up to 39.4%. Additional studies to investigate the geo-risk of GCHP systems in subarctic regions suggest that these have a low risk and can reduce ground subsidence and help to stabilise permafrost [36,37]. However, the long-term thermal depletion may become an issue and solutions need to be found.

Given the technical feasibility and economic attractiveness of GCHPs, Kuujjuaq (***Figure 6***) carried out a geothermal heating project for the community's swimming pool as part of the federal program Indigenous Off-diesel Initiative. The system is a horizontal closed-loop GCHP of 30 kW. Additionally, a new research station of the Centre d'études nordiques (CEN) is under construction at Umiujaq (Quebec; ***Figure 6***) and the integration of a mix of renewable technologies (biomass, solar, and geothermal) is foreseen. Moreno *et al.* [35] suggested that this mix can be a cost-effective option since the levelized cost of energy (LCOE) of a mix of renewable heating systems can be comparable to that of oil furnaces, but with lower CO_2 emissions (***Table 2***).

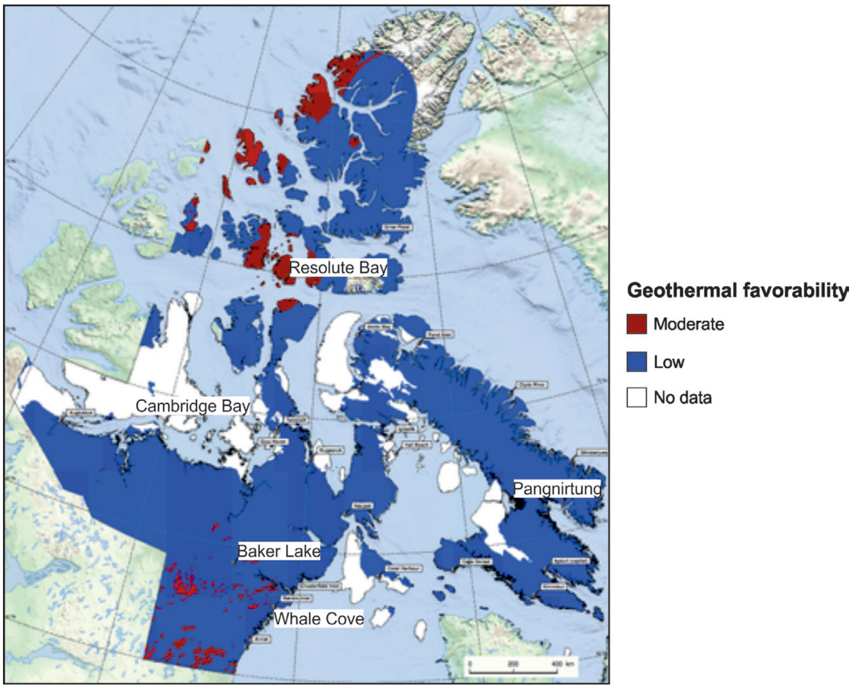

Figure 5: Nunavut geothermal favourability map (after [23]). The reader is referred to Figure 1 for geographical location.

Table 1: Summary of net present cost (NPC) and CO_2 emissions for different solutions to heat a 5-occupant residential dwelling in Kuujjuaq (Quebec; [31]).geographical location.

Heating solution	*NPC (k$)*	*CO_2 emissions (t)*
Fuel oil	*277*	*29*
Compression heat pump *70% of electricity by solar PV panels* *30% from diesel power plant*	*203*	*18*
Compression heat pump *100% of electricity by solar PV panels*[1]	*179*	*15*
Compression heat pump *100% of electricity by diesel power plant*	*259*	*26*
Absorption heat pump	*231*	*25*

PV – Photovoltaic. The cost is in Canadian dollars (CAD).

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[1] *Assuming energy storage (battery).*

Table 2: Summary of NPC, levelized cost of energy (LCOE) and CO2 emissions for the different heating solutions in Umiujaq [35]

Heating solution	*NPC (k$)*	*LCOE ($/kWh$_{th}$)*	*Carbon emissions (t)*
100% Oil furnace	*364*	*0.21*	*27*
50% Biomass + 50% GCHP *100% of electricity by solar PV panels*	*373*	*0.26*	*0.2*
70% Biomass + 30% GCHP *100% of electricity by solar PV panels*	*346*	*0.23*	*0.3*

The cost is in Canadian dollars (CAD).

3.2. Borehole thermal energy storage (BTES)

A numerical study coupled to a 50-year life-cycle cost analysis demonstrated for the first time in a polar climate that borehole thermal energy storage (BTES) can be viable for heating drinking water in a subarctic climate utilising seasonal solar energy storage [38]. The numerical simulations suggested that solar fraction of 45 to 50% and heat recovery of more than 60% can be achieved by the 3rd year of operation. This would result in annual savings of 7,000 l of diesel consumption. Furthermore, the life-cycle cost analysis suggests that a specific incentive programme can guarantee similar NPC and LCOE compared to the current diesel situation (***Table 3***).

Recovery and seasonal storage of waste heat from diesel generators can be another viable option for remote northern communities. Ghoreishi-Madiseh *et al.* [39] showed that 350 MWh of heat can be annually stored and provided by a BTES system relying on waste heat. The system is estimated to have a capital expenditure (CAPEX) of $ 235,000, with a payback period below 5 years. Such a system can led to an annual decrease of about 90 tonnes of CO_2 and about $ 48,000 of savings.

3.3. Enhanced/engineered geothermal systems (EGS)

Research indicated that EGS can be both technologically feasible and economically viable for Canadian remote northern communities [4,6,7,40]. The thermal energy extracted from the subsurface may be sufficient to meet the communities' heating (and electricity) needs and the LCOE can be comparable to that of the oil furnaces (***Table 4***) but with lower CO_2 emissions. Majorowicz and Grasby [6] estimated that Canadian and US EGS projects can potentially save 164 t/day of CO_2 and 88,000 m^3/day of natural gas.

3.4. Hybrid geothermal systems

Several communities in Canada's north are making growing use of solar and/or wind energy to meet part of their power needs [41,42]. Recent cost data is not publicly available, and is site specific, but discussions with experts indicate that they are most likely cheaper than geothermal, especially compared to EGS. However, their intermittent nature means they

Table 3: Summary of NPC and levelized cost of energy (LCOE) for the different BTES scenarios studied for the drinking water facility in Kuujjuaq [38]

Scenario	NPC ($)	LCOE ($/kWh$_{th}$)
Fuel oil	2,054,682	0.214
BTES 224	3,419,089	0.357
BTES 224 subsidised	2,326,917	0.243
BTES 37	2,846,336	0.297
BTES 37 subsidised	2,040,541	0.213

The cost is in Canadian dollars (CAD).

Table 4: Summary of LCOE for an EGS in Kuujjuaq [40] and northern Canada [4].

Heating solution	LCOE ($/MWh)		
	Optimistic	Likely	Pessimistic
Fuel oil furnaces (Kuujjuaq)	190		
EGS (Kuujjuaq)	54 - 145	83 - 265	170 - 626
EGS (northern Canada)	50 - 80		

The cost is in Canadian dollars (CAD).

require expensive energy storage and full-scale diesel power backup, which is often not considered when calculating their LCOE. In addition, the long, dark season and icing issues make wind and solar ineffective when energy demand is greatest.

Hybrid systems, comprising geothermal energy combined with other renewables like wind and solar (also biomass, hydrokinetic, etc.) and energy storage technologies (e.g., batteries, compressed air, seasonal thermal energy storage; [38,43]), are a prospective energy solution for remote northern communities (***Figure 7***). They have the potential to provide stable, baseload power and heat with increased environmental benefits at reduced cost compared to stand-alone geothermal systems and diesel systems with intermittent renewables [44].

Wind and solar can meet more of a communities' energy needs in the summer when their potential is greater. Therefore, the geothermal system can be optimised by taking advantage of the lower ambient temperature in the colder months, which means a lower input temperature (i.e., shallower and cheaper) is required. Reducing the draw on the geothermal reservoir for heat and power can extend its lifetime and thus reduce its cost. Therefore, Dehghani-Sanij and Wigston [45] have been conducting a techno-economic feasibility analysis of a hybrid geothermal system for Fort Liard, NWT (***Figure 7***).

4. Discussion and conclusions

The development of geothermal and other renewable energies can bring important socio-economic benefits to northern communities. However, despite the potential benefits, geothermal deployment is still a complex task in northern communities, with buildings not prepared for the technology and with a lack of training for the system operation and maintenance. Additionally, the deployment cost is still high, and more work is needed to make geothermal systems cost-efficient compared to diesel (***Figure 8***).

Nevertheless, previous research showed that solar-assisted GCHP can be a viable short-term solution to provide energy savings for most communities located in a subarctic climate [31,33-35]. Dealing with building loads that are unbalanced and require heating only plus ground conditions near permafrost are the main challenges that can be faced for properly sizing systems. Deep resources harnessed with EGS technologies are medium to long-term options that may have enough capacity to meet the entire electricity and heating requirements of isolated communities [4,40]. Here, the main challenge is to evaluate subsurface conditions at a

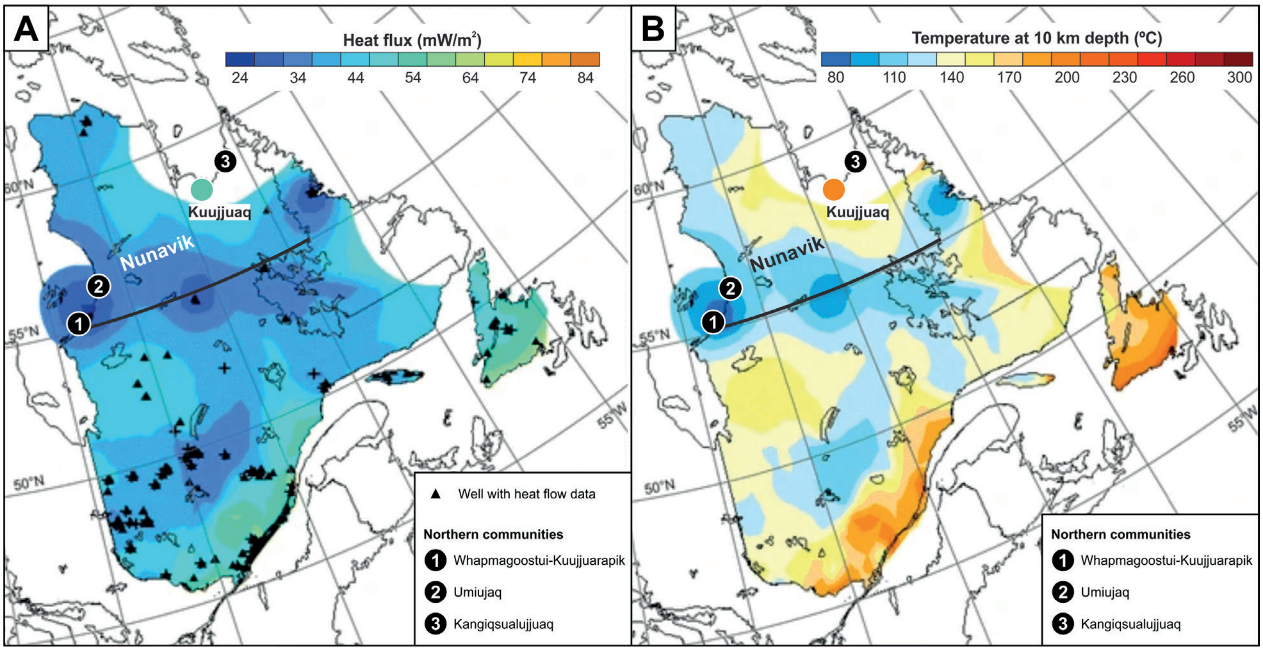

Figure 6: (A) Heat flux map and (B) predicted temperature pattern at 10 km depth in Quebec (after [24]). The reader is referred to Figure 1 for geographical location.

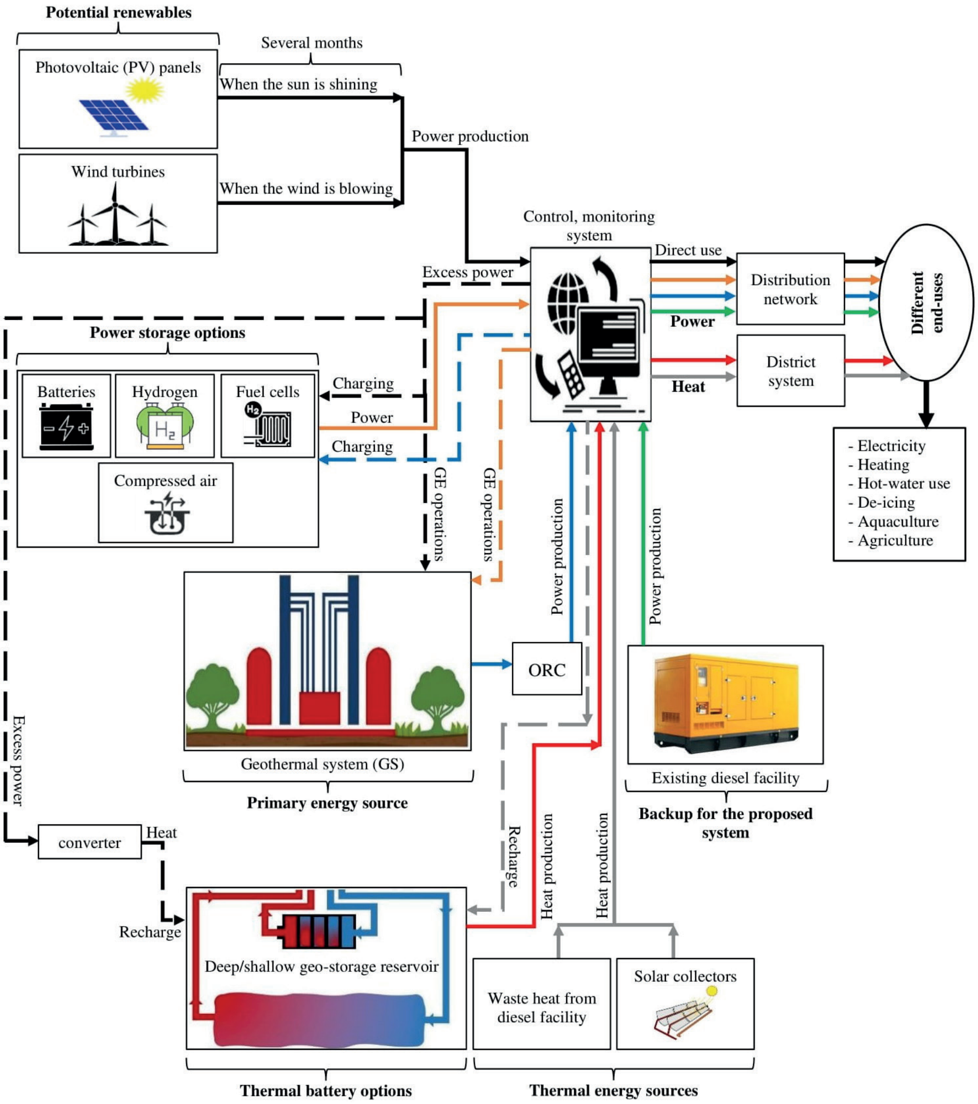

Figure 7: A proposed hybrid geothermal system for Fort Liard, NWT – as an example [45].

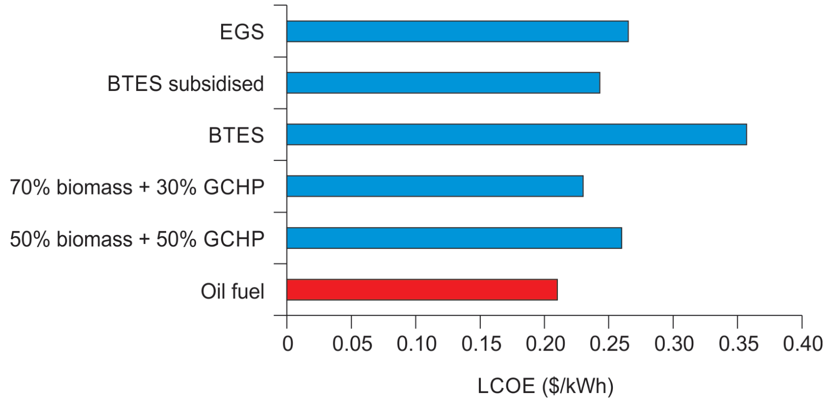

Figure 8: Estimated LCOE of the different heating solutions studied [35,38,40]. Oil fuel price from 2019, in Canadian dollars.

depth of several kilometres where deep boreholes are often non-existent but are needed to trigger development interest.

In summary, geothermal energy can be an option for remote northern communities if Indigenous peoples are interested in such development. Further geothermal exploration and research is needed to decrease uncertainty and risk. Drilling of deep wells and data acquisition campaigns should be designed at a community scale level. Numerical simulations of geothermal technologies can also help predict their performance and find the optimal design to meet the power and heating needs of Indigenous communities in the context of cost, environmental impact, reliability and ease of use/repair.

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Geothermal resources research in a granitic basement - the Braga area case study (NW Portugal)

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Geothermal resources are increasingly being considered as a strategic alternative in energy production, especially with the latest geopolitical developments. The densely populated Braga region, in NW Portugal, is endowed with a geostructural setting that enables the existence of several thermal water occurrences, spatially associated with a deep-rooted structure – the Vigo-Régua shear zone, set in a granite context. Given the latest advances in geothermal energy production, it is possible to predict a mid- to long-term implementation of geothermal energy production in the vicinity of that deep rooted structure. Although strongly encouraging, the exploratory geophysical, geochemical and geological data are still insufficient to deliver a definitive frame of the potential energy associated with the estimated reservoirs. Ongoing work combining gravimetric, radiometric and geochemical data will provide a better understanding of the deeply concealed structures.

Les ressources géothermiques sont de plus en plus considérées comme une alternative stratégique dans la production d'énergie, en particulier compte tenu du contexte géopolitique récent. La région densément peuplée de Braga, au nord-ouest du Portugal, est située dans un contexte granitique spatialement associé à une structure enracinée - la zone de cisaillement Vigo-Régua. Ce contexte géologique et structural a permis le développement de plusieurs occurrences d'eau thermale. Compte tenu des dernières avancées en matière de production d'énergie géothermique, il est possible de prévoir une mise en œuvre à moyen et long terme de la production d'énergie géothermique à proximité de cette structure profonde. Bien que fortement encourageantes, les données géophysiques, géochimiques et géologiques exploratoires sont encore insuffisantes pour fournir un cadre définitif de l'énergie potentielle associée aux réservoirs estimés. Des travaux en cours combinant des données gravimétriques, radiométriques et géochimiques permettront de mieux comprendre les structures profondément enfouies.

Los recursos geotérmicos se consideran cada vez más como una alternativa estratégica en la producción de energía, especialmente con los últimos desarrollos geopolíticos. La región densamente poblada de Braga, en el noroeste de Portugal, está dotada de un entorno estructural que permite la presencia de aguas termales, asociadas espacialmente con una estructura profunda en un contexto granítico: la zona de falla Vigo-Régua. Dados los últimos avances en la producción de energía geotérmica, es posible predecir una implementación a mediano y largo plazo de la producción de energía geotérmica en las cercanías de esa estructura de raíces profundas. Aún cuando los datos geofísicos, geoquímicos y geológicos exploratorios son muy alentadores, son insuficientes para brindar un marco definitivo del potencial geotérmico asociada con los yacimientos. El trabajo en curso que integra datos gravimétricos, radiométricos y geoquímicos proporcionará una mejor comprensión de las estructuras profundas por explorar.

1. Introduction

Geothermal resources are considered a sustainable and environmentally friendly alternative to produce energy. The European Federation of Geologists (EFG) states that geothermal energy, both shallow and deep, is part of the answer to meet the issue of efficient renewable energy production [1].

The exploration of geothermal resources combines a set of different methodologies and techniques, as described in [2], in which the use of geophysics has an important specific role. However, there is always a significant degree of uncertainty that creates gaps that need to be filled with consistent geological models [3]. Geophysical methods like gravimetry can be used to obtain useful information regarding the deep geostructural setting of geothermal sites, and therefore its fluid circuits. Also, radiometry can be used to detect radiogenic heat generating rocks, potential sources of underground heat.

The north of Portugal seems to be a suitable area for the exploitation of geothermal resources due to its mean geothermal gradient of 35.5 °C/km [4] and a mean heat flow value of 95 mW m^{-2}, derived from borehole measurements [5].

The Braga region, located in NW Portugal, is a zone with well-defined geostructural indicators (***Figure 1***). These indicators are the presence of a deep-rooted structure, the Vigo-Régua shear zone, with its associated secondary structural pattern of faults and fractures; the existence of several thermal water occurrences spatially associated with the main faults (***Figures 2,3***), as well as

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other structural settings; the definition of strong gravimetric anomalies correlatable with the existing geology; and the indication of significant temperatures derived from geothermometry. The application of chemical geothermometers in the region of Braga has allowed the temperature estimate approach of the geothermal reservoirs that feed the researched thermal water occurrences, as well as the its circulation depth. Several studies have demonstrated the suitability of the application of environmental isotopes in the characterisation of geothermal reservoirs in different zones of the Maciço Antigo in northern Portugal [6-10].

The estimated reservoir temperature for the studied sites allows us to predict the feasibility of using direct heat and to promote the eventual electricity production, considering the Lindal diagram [11]. Good results could also be obtained with other complementary techniques, such as electric resistivity and induced polarisation, in specific settings.

This research intends to upscale the existing knowledge regarding the Enhanced Geothermal System (EGS) potential of a specific region of the Variscan granitic basement, as classified in [12], attempting – although in an exploratory approach – to define functional regional guides for geothermal research and exploration.

According to Nicholson [13], systems with temperatures below 150 ºC are considered low-temperature systems. The deduced water temperature of the studied Portuguese thermal occurrences is mainly below this threshold, with some values above it. As stated before, these results need to be addressed with caution.

The studied area is densely populated, with annual energy consumption of 3×10^9 kWh in the broader region and a 7×10^8 kWh in the city surroundings in 2020, which is equivalent to 2.1×10^5 tonnes of oil equivalent [14]. The main motivation of this work is to better understand the local deep geostructural setting within the scope of geothermal resources research tools development.

2. Geological setting

The Braga area (Iberian Peninsula; NW Portugal) is located in the Central Iberian Zone (CIZ) of Portugal and in the Galicia–Trás-os-Montes Zone (TMZG) (*Figure 1*) [15].

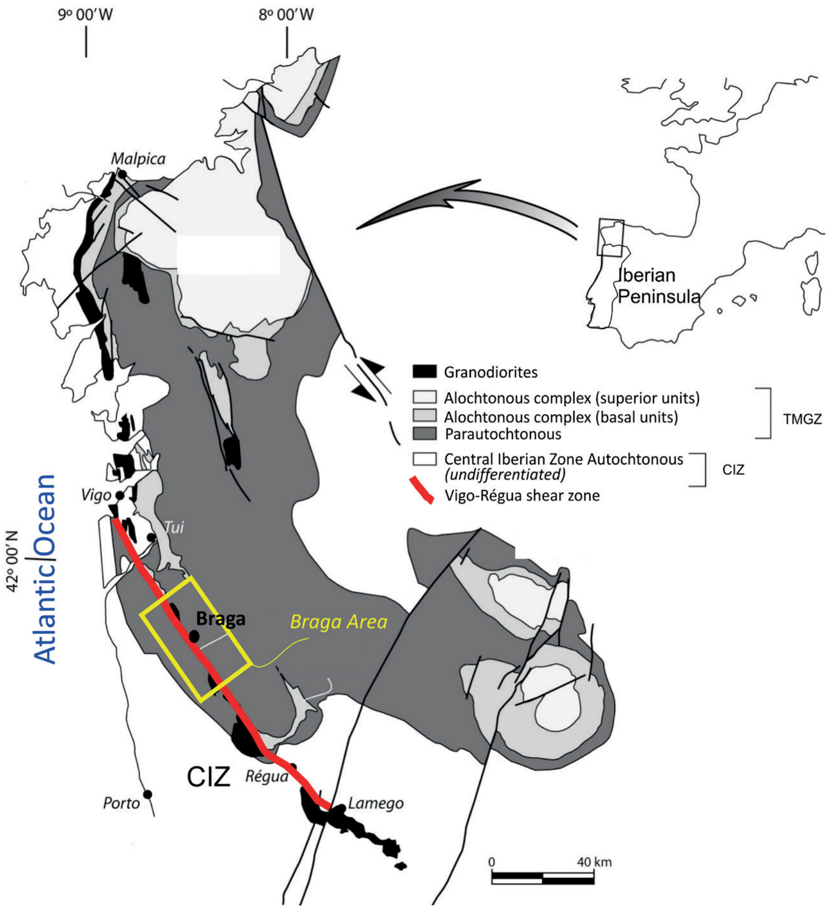

Figure 1: Geological-structural setting of the study area.

The CIZ was formed in the Variscan Orogeny, resulting from the continental collision between the continents Gondwana and Laurussia, which began at the end of the Silurian and beginning of the Devonian, characterized by subduction and obduction mechanisms of the oceanic crust [16]. The Variscan cyclebegan with the opening of oceans bordered by passive margins (540–420 Ma), followed by the beginning of the subduction in the Palaeozoic Oceans with the subordinate opening of marginal basins post-arc and ophiolitic blade obduction (420–390 Ma) and high pressure thermometamorphic events. Subsequently, continental collision and orogeny occurred with sedimentary and tectonic polarity oriented towards the foreland zones (390–300 Ma), accompanied by thermal anomalies, generating abundant granitoids and high-temperature metamorphism, followed by a transcurrent intracontinental deformation and localised orogenic collapse (300–270 Ma) [17]. Variscan deformation is characterised by polyphasic processes and is divided into three tectonic phases, D1, D2 and D3 [16,17,18]. The D1 phase generated folds with NW-SE predominant orientation, but in allochthonous, parautochthonous or autochthonous stratigraphical formations, generates folds with different orientations and vergence, with folds with vertical axial plane in the autochthonous and slightly vergent in the parautochthonous. The D2 phase occurred close to the D1 phase, with the formation of lying folds facing SE being well represented in the allochthonous and the parautochthonous [16], with the development of subhorizontal foliation (S2) [18]. The D3 phase, unlike the previous ones, occurred in all terrains, autochthonous, parautochthonous and allochthonous.

At a regional level, vertical and NNE-SSW oriented corridors and ductile-brittle and brittle shear zones are defined. Still in this phase, previous structures that possibly developed in D1 or D2 (Vigo-Régua shear zone) were reactivated in a transcurrent regime [19]. The Variscan orogeny originated a crustal thickening that produced granitic magmas by anatexis. The Portuguese Variscan granites are synorogenic and can be divided into two groups, two-mica granites and biotitic granites [20]. Two-mica granites are syntectonic relatively to the D3 (syn-D3)

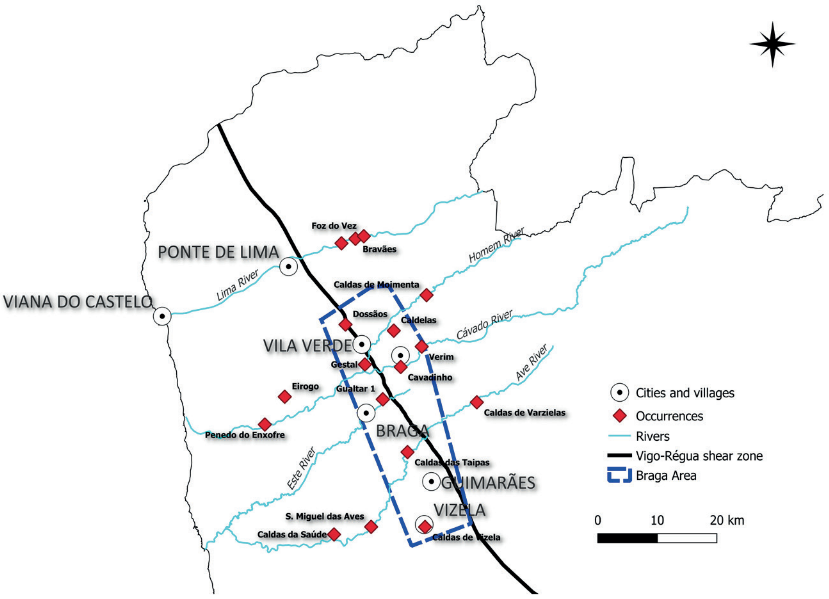

Figure 2: Identified thermal occurrences in the vicinity of the Vigo-Régua shear zone from the Braga region.

Table 1: Data from thermal water occurrences in the Braga region.

	Temperature (°C)	pH	Depth (m)	Water Type	Use
Caldelas(a)	31	8.2	179	Bicarbonate	Spa
Cavadinho/Crespos(b)	20.4	9.25	0	Sulphureous	None
Verim(b)	<20	8.86	0	Sulphureous	None
Gestal(b)	15.5	8.9	0	Sulphureous	None
Caldas das Taipas(b)	30	8.0	n.d.	Sulphureous	Spa
Caldas de Moimenta(a)	21	9.1	n.d.	Sulphureous	Spa
Caldas de Vizela(a)*	43.5	9.34	62	Sulphureous	Spa
Gualtar(c)	18.0	7.41	0	Sulphureous	None

*Legend: (a) [24], (b)[27], (c)[26]; *(b)65ºC registered historically*

Variscan deformation phase, and are generally located along the core of regional bends D3, with NW-SE direction (D3, last phase of Variscan ductile deformation). They are usually leucocratic granites, with muscovite and primary biotite, resulting from the wet crystallisation of peraluminous magmas, originating from a mesocrustal level [20]. The second group, biotitic granites, originate deeper in the crust and correspond to relatively dried magmas, and if muscovite occurs in this group, it is of secondary origin [21]. Biotitic granites are mainly controlled by D3 shears and late Variscan tectonic structures. The emplacement period of granites, relative to the D3 phase, can be syn-D3 (320–313 Ma), late-D3 (311–306 Ma), late to post-D3 (300 Ma) or post-D3 (299–290 Ma) [22].

In the study area, the relief morphology is marked by tectonics, where the lithologies have been strongly affected by the Variscan NNE-SSW and NW-SE fracturing, and reactivated by Alpine movements that generated their own ENE-WSW fracture network [23]. The granitoids emplacement that outcrops in this area was mainly conditioned by the Variscan phase. Late-Variscan tectonics is marked by the effect of maximum compression with NE-SW orientation caused by NW-SE and fracturing well marked in this area by the great alignments of the river network [23].

The regional setting of the study area can be observed in Figure 1, where the major tectonic-stratigraphic units are identified.

The Vigo-Régua ductile shear zone corresponds to the southernmost segment of a larger system (the ductile shear zone of Malpica-Lamego); (***Figure 1***), with a dominant NW-SE orientation parallel to the Variscan Chain on the NW of the Iberian Peninsula and with a total extension of 275 km [20].

The Vigo-Régua ductile shear zone segment has a multiphase kinematic interpretation within the Variscan orogeny: left-hand movement in D1 and D2 (370–310/315 Ma) and right-hand movement in D3 (310/315–300 Ma) [20]. In D1, a thrusting event is identified, followed by an episode changing the structural vergence, previous to D3. This shear zone has a sub-vertical foliation or W-slanted penetration and a sub-horizontal stretching lineation [19]. This shear develops along parautochthonous and associated granitic rocks. The granodiorite rocks are structurally controlled by this shear zone [19].

2.1. The Braga Area

The studied area is located within the Cávado and Ave River watersheds, in NW Portugal (***Figure 2***), included in a broader unit defined as Portuguese Hydrographic Region 2 (RH2). The combined watershed area is of roughly 3,060 km^2.

The average annual flow on the Cávado and Ave Rivers watershed is about 3,402 hm^3. It is estimated that the rainfall in the combined catchment area is on average 1,788 mm/year, ranging from 968 mm to 3,253 mm [23], which guarantees the constant recharge of groundwater systems. There are different thermal water occurrences located near and spatially related to the Vigo-Regua shear zone (***Figure 2***). Data from occurrences surrounding the study area can be observed in Table 1.

The geomorphology of the area is mainly characterised by a typically alveolar morphology with extensive and wide valleys as well as orographic systems with steep slopes, with graben type and reliefs of the Horst as a result of a base geologically markedly granitic and strongly controlled by tectonics [24].

The NNE–SSW and ENE-WSW structures are well marked in the orientation of the rivers and tributaries (***Figure 3***) as well as in the main elevations as a result of the late-Variscan tectonic action and the Alpine movements.

The Cávado deposits occur mainly in the river's right margin, in a graben morphological depression, as well as in the Ave River. The strong NW-SE tectonic control can be observed in the granitic plutons outcropping shapes (***Figure 3***). Also, the E-W valleys tend to be filled with detrital materials, suggesting graben-like structures associated with these late-Alpine valley directions. The metasediments only outcrop on the west block of the Vigo-Régua shear zone, which suggests the upward movement of the East block

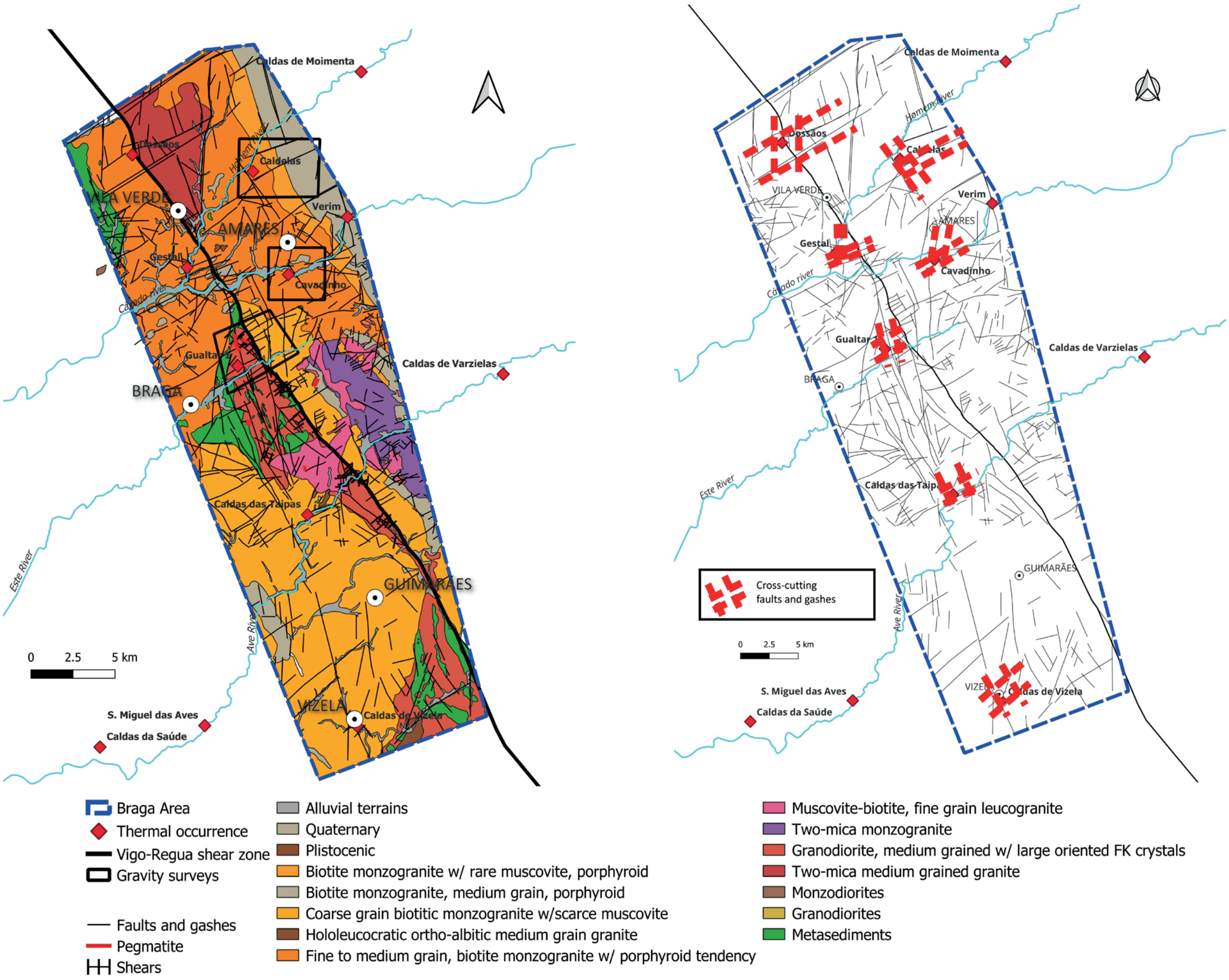
Caldas de Moimenta
Dossãos
Caldelas
Homem river
VILA VERDE
Verim
AMARES
Gestal
Cavadinho
Cávado river
Gualtar
BRAGA
Caldas de Varzielas
Caldas das Taipas
GUIMARÃES
Este River
Ave River
0
2.5
5 km
S. Miguel das Aves
Caldas da Saúde
VIZELA
Caldas de Vizela
Cross-cutting faults and gashes
Braga Area
Thermal occurrence
Vigo-Regua shear zone
Gravity surveys
Faults and gashes
Pegmatite
Shears
Alluvial terrains
Quaternary
Plistocenic
Biotite monzogranite w/ rare muscovite, porphyroid
Biotite monzogranite, medium grain, porphyroid
Coarse grain biotitic monzogranite w/scarce muscovite
Hololeucocratic ortho-albitic medium grain granite
Fine to medium grain, biotite monzogranite w/ porphyroid tendency
Muscovite-biotite, fine grain leucogranite
Two-mica monzogranite
Granodiorite, medium grained w/ large oriented FK crystals
Two-mica medium grained granite
Monzodiorites
Granodiorites
Metasediments

Figure 3: Geological map of the study area [25][26][28][29][30].

Table 2: Water temperature (°C).

	Qz geothermometer	***Na/K geothermometer***	***Measured Temperature***
Caldelas(a)	*71*	*153*	*31*
Cavadinho/ Crespos(b)	*77*	*59*	*20.4*
Gualtar	*no data*	*no data*	*18*

Legend: (a)[24] (b) [27]

of this right-hand structure. In the same figure a simplified view of the brittle structures (faults, fissures and gashes) is shown, highlighting crosscutting nodes near known occurrences. Also, the outcropping lithologies are identified.

When observing this figure, it is quite clear that cross-cutting fault and gash structures of WSW-ENE with NNW-SSW directions are associated with the known occurrences, with the exception of the Cavadinho thermal occurrence. This structural criterion was a base for the selection of the three studied occurrences, because of the contrast with the surrounding rock, induced by negative Bouguer anomalies expected in deeply fractured zones [31]. Also, cumulatively, these occurrences are located near urban centres and geothermometric data are available. Isotopic studies [24] and [27] allowed an approach towards the deeper circulation water temperature. The results can be viewed with "optimistic" and "pessimistic" approaches, and need to be addressed with caution. The range of values for water temperature estimates range from 59 ºC to 132 ºC applying the quartz geothermometer [24] and [27] and from 59 ºC to 153 ºC using the Na/K geothermometer [24] and [27]. These estimates are well above the natural spring water temperatures, as shown in ***Table 2***. The geology of each one of the three selected sites can be observed in ***Figure 4*** (From north to south: Caldelas, Cavadinho, Gualtar).

The Caldelas site geology consists of three outcropping granites, with NW-SE direction, cross-cut by NW-SE and WSW-WNE faults and gashes. The Cavadinho site has only one outcropping granite, with crosscutting faults and gashes with NNE-SSW and WSW-ENE directions. The Gualtar site has a more complex geology with three outcropping granites, as well as metasediment, and is crossed by the Vigo-Regua shear zone.

3. Materials and Methods

The present study is comprised of several tasks: site selection based on crosscutting structures and thermal occurrence locations, collection and interpretation of gravimetric data and interpretation of radiometric data.

An exploratory approach is considered using combined geophysical tools. Considering the extensive demography and highly urban areas on the studied region, the use of electromagnetic and electric geophysical methods is considered unsuitable due to logistics and signal interference. The choice of geophysical tools fell on the use of gravimetry and radiometry, with the first one aiming to detect density contrasts related to outcropping structures/lithologies that could point out possible reservoirs in low density areas. Radiometry is used with the main objective of revealing radiation anomalies related to highly radiogenic granites [31], which are also structurally controlled. The database [33] was used to model the radiometric background of the study area and selected sites. The gravimetric surveys were conducted using a Pioneer, Worden 679, model 155 gravimeter with full DGPS follow-up. Specifics on the conducted gravity surveys can be consulted in References [34] and [35].

4. Results

Figure 5 presents and compares the results from the gravity survey, expressed in complete Bouguer anomaly (mGal) and the radiometric background (nGy/h). A clear relation between radiometric and gravimetric highs can be observed for the Caldelas site. The known thermal occurrence is located in a sudden transition zone between high and low anomalies.

The results obtained for the Cavadinho site (***Figure 6***) also show that a clear relation between radiometric and gravimetric highs can be observed, although this is not quite as conspicuous as at the Caldelas site. Here also the known thermal occurrence is located in a transition zone between high and low anomalies.

The Gualtar site results (***Figure 7***) show a more diffuse spatial relation between

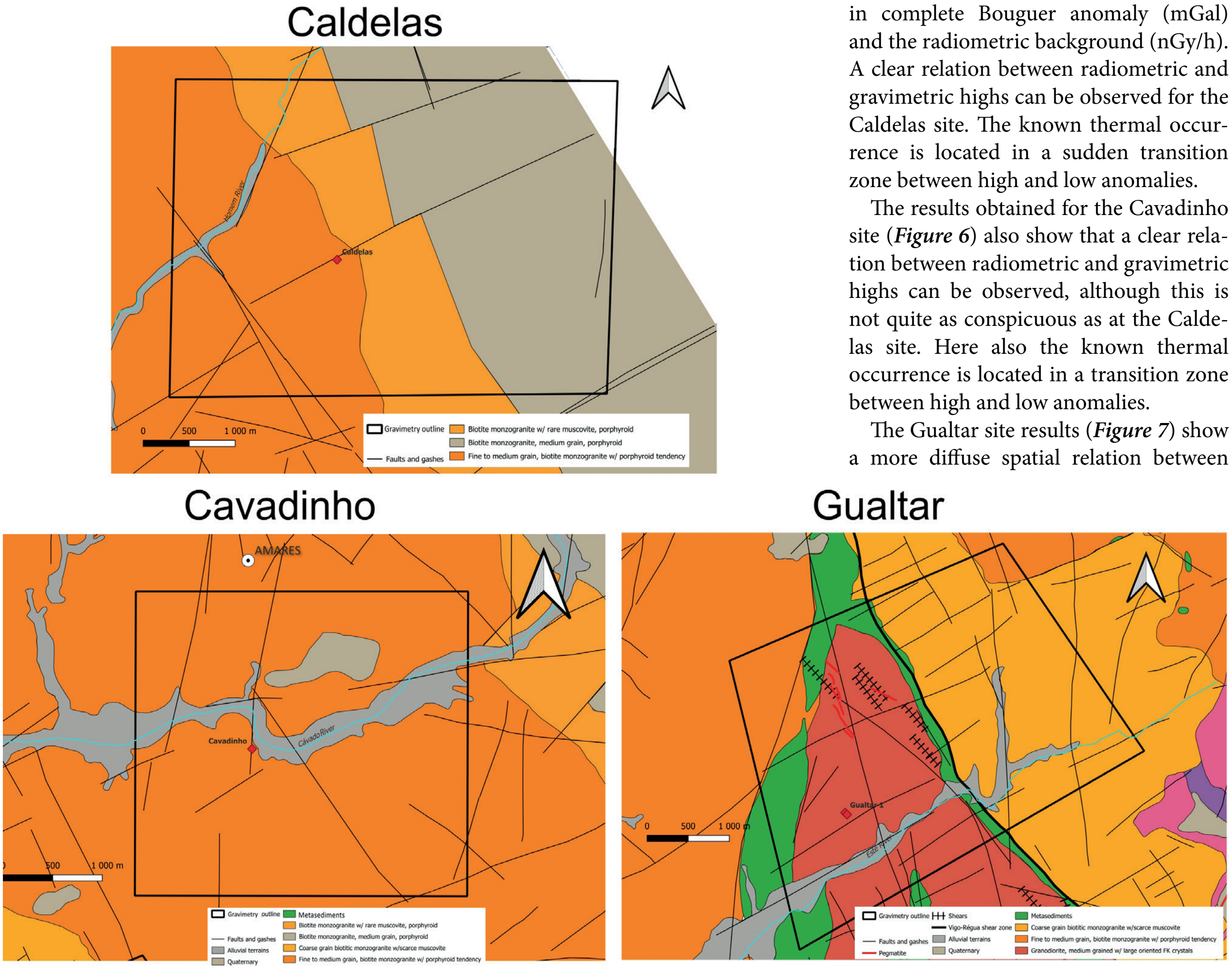
Caldelas
Homem River
Caldelas
0
500
1 000 m
Gravimetry outline
Faults and gashes
Biotite monzogranite w/ rare muscovite, porphyroid
Biotite monzogranite, medium grain, porphyroid
Fine to medium grain, biotite monzogranite w/ porphyroid tendency
Cavadinho
AMARES
Cavadinho
Cávado River
500
1 000 m
Gravimetry outline
Faults and gashes
Alluvial terrains
Quaternary
Metasediments
Biotite monzogranite w/ rare muscovite, porphyroid
Biotite monzogranite, medium grain, porphyroid
Coarse grain biotitic monzogranite w/scarce muscovite
Fine to medium grain, biotite monzogranite w/ porphyroid tendency
Gualtar
Gualtar 1
Este River
0
500
1 000 m
Gravimetry outline
Shears
Vigo-Régua shear zone
Faults and gashes
Pegmatite
Alluvial terrains
Quaternary
Metasediments
Coarse grain biotitic monzogranite w/scarce muscovite
Fine to medium grain, biotite monzogranite w/ porphyroid tendency
Granodiorite, medium grained w/ large oriented FK crystals

Figure 4: Geological setting of the selected sites.

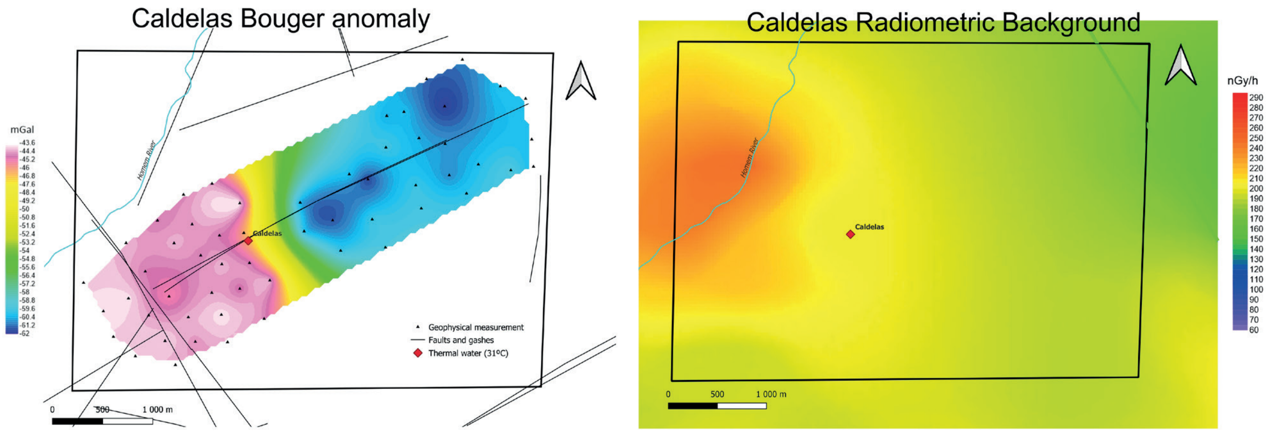

Figure 5: Bouguer anomaly and radiometric background at the Caldelas site.

radiometric and gravimetric highs. The known thermal occurrence is located near a sudden transition zone between high and low anomalies.

A broader view of the results can be attained in ***Figure 8***. There is a clear association between known thermal occurrences and radiometric highs.

The comparison of gravimetric and radiometric data points to the existence of a spatial relationship between the location of thermal water occurrences and radiometric maximum values. Similarly, there is an overlap of the gravimetric anomaly maximum values – indicative of higher density zones – and the radiometric maximum values. Thermal water occurrences are also associated spatially with contrasting zones of high and low gravimetric anomalies. Low radiometric values are associated with granodiorites, leucogranites and metasediments from the area, while high values are mainly related with biotite monzogranites.

5. Discussion

The results generated by the conducted exploratory research, although encouraging, must be viewed with caution. In fact, there are many questions that arise from the obtained results. The scale and detail of the gravimetric and radiometric surveys must be increased in order to show small anomalies related to the outcropping geo-structural data. Also, the scale and definition of the geo-structural mapping must be improved, at least in the already studied sites and in the areas near the thermal water occurrences. The now defined regional exploration guides, which consist of overlapping gravitic lows with radiometric highs and cross-cutting brittle structures in the vicinity of a large polyphasic shear zone, must be thoroughly tested with a refining of geophysical surveys, as well as geological mapping combined with seismic data analysis.

Despite the high annual water recharge of the studied area, there is no consensus concerning the origin of thermal water (e.g. [6], [10], [27]), and our results neither support nor reject the hypothesis of deep-water circulation through tectonic structures, which is the most scientifically accepted. The low gravimetric anomalies surrounding the thermal water occurrences are interpreted as the result of the occurrence of porous/fractured rocks acting as a deep reservoir with a not fully understood origin. The highest radiometric values are probably related to highly radiogenic rocks, a possible source of heat [36]. Thus, these occurrences can be the result of the decay of dense radiogenic rocks with nearby reservoirs induced by the tectonic setting endowed by the Vigo-Régua shear zone and associated faults and gashes. The low radiogenic rocks can act as a cap to the heat generated by the most radiogenic ones.

The temperature range of the selected water occurrences is sufficient to allow

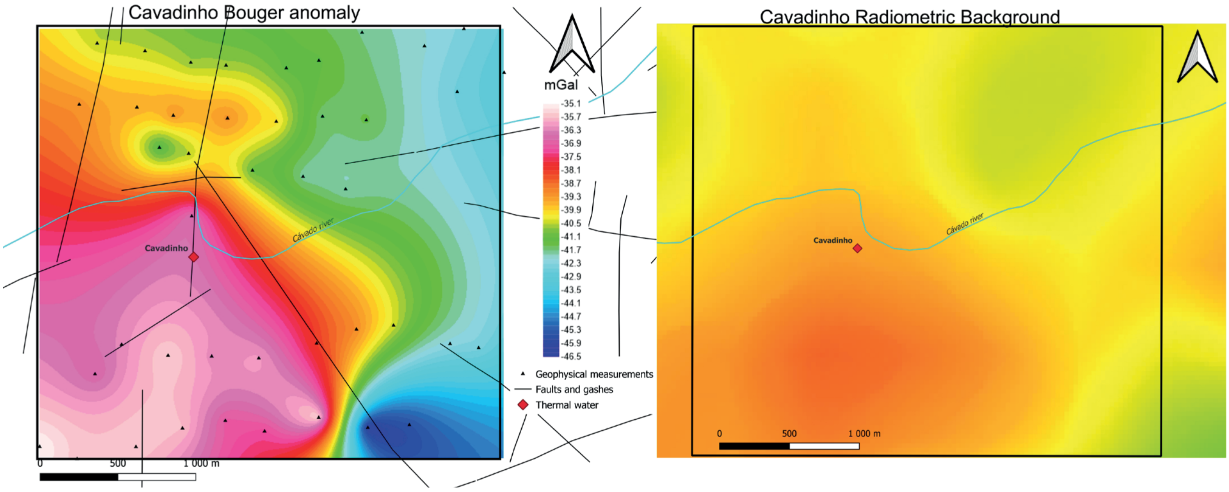

Figure 6: Bouguer anomaly and radiometric background at the Cavadinho site.

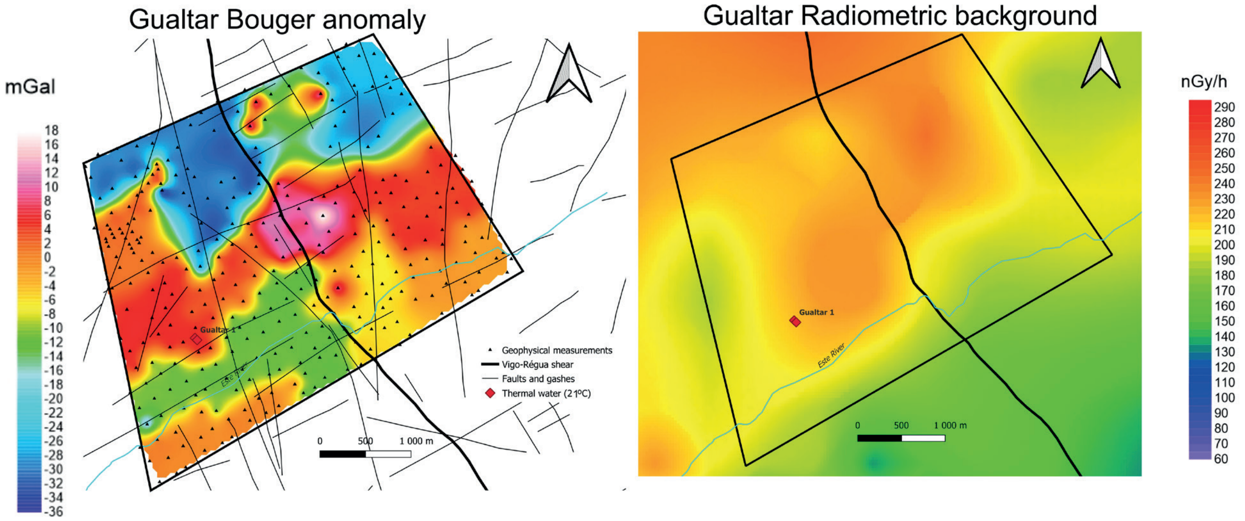

Figure 7: Bouguer anomaly and radiometric background at the Gualtar site.

electricity generation in binary geothermal power plants [11]. Also, some of the water samples were collected in natural springs and others in boreholes. The comparison of water temperature from boreholes and natural springs allows to state that water temperature increases significantly with depth.

Further studies must be carried out in order to obtain a representative framework of water flow production in these occurrences, which are not known or fully disclosed, mainly the ones that are being currently exploited for balneotherapy and spas.

6. Conclusions

This study was carried out within the Maciço Antigo geotectonic unit in Portugal, focusing on a portion of its Variscan granitic basement which has a geostructural setting that enables the existence of several thermal occurrences. However, the risk of exploration increases considerably in moving away from known hot spring occurrences [36]. There are in-depth geological alteration processes associated with thermal water fluids, unperceived at the surface (non-outcropping), that are detectable through the use of geophysical exploration tools. Local geological singularities will determine the conditions for groundwater circulation and storage. Some parts of the Portuguese territory, namely within its granitic basement, present favourable geostructural indicators for the implementation of stimulated geothermal energy, when compared with other European sites where this technology is being used, despite the large gaps in the detailed knowledge of the underground reservoirs [37].

It is possible to foresee geothermal resource exploration in the vicinities of the deeply rooted Vigo-Régua shear zone, within the Cávado watershed [38], considering the existing data, especially data obtained from geothermometers. However, information on the deep geometry of the Vigo-Régua shear zone and the geothermal fluid circulation mechanisms is scarce. Further research and data collection from combined geostructural, geophysical surveys, hydrogeochemistry and geothermometry of the known regions will allow the determination of drilling targets away from already identified thermal water occurrences and the discovery of geostructural settings favourable for EGS and/or deep geothermal exploration It is also conspicuous that the estimated temperature calculated from geothermometers and from boreholes is much higher than the water temperature measured at the surface (in springs). This situation needs to be clearly understood, especially considering the deep reservoir and its link to the deeply rooted Vigo-Régua shear zone, assumed to be the structure that controls the heat pulses and geothermal circuits by seismic pumping at a regional scale. Also, this will help the identifcation of potentially anomalous geothermal gradients. The tectonic control of thermal water occurrences is evident, as shown by the radiometric and gravimetric anomalies and their relationship to the configuration of regional structures. These indicators, regional structures, and gravimetric and radiometric anomalies may be used as future guides for the exploration of regional geothermal resources.

The potential of the studied area for Enhanced Geothermal Systems (EGS) and/or deep geothermal is plausible, considering the geological setting, thus enabling the production of heat and eventually electricity from this renewable energy source.

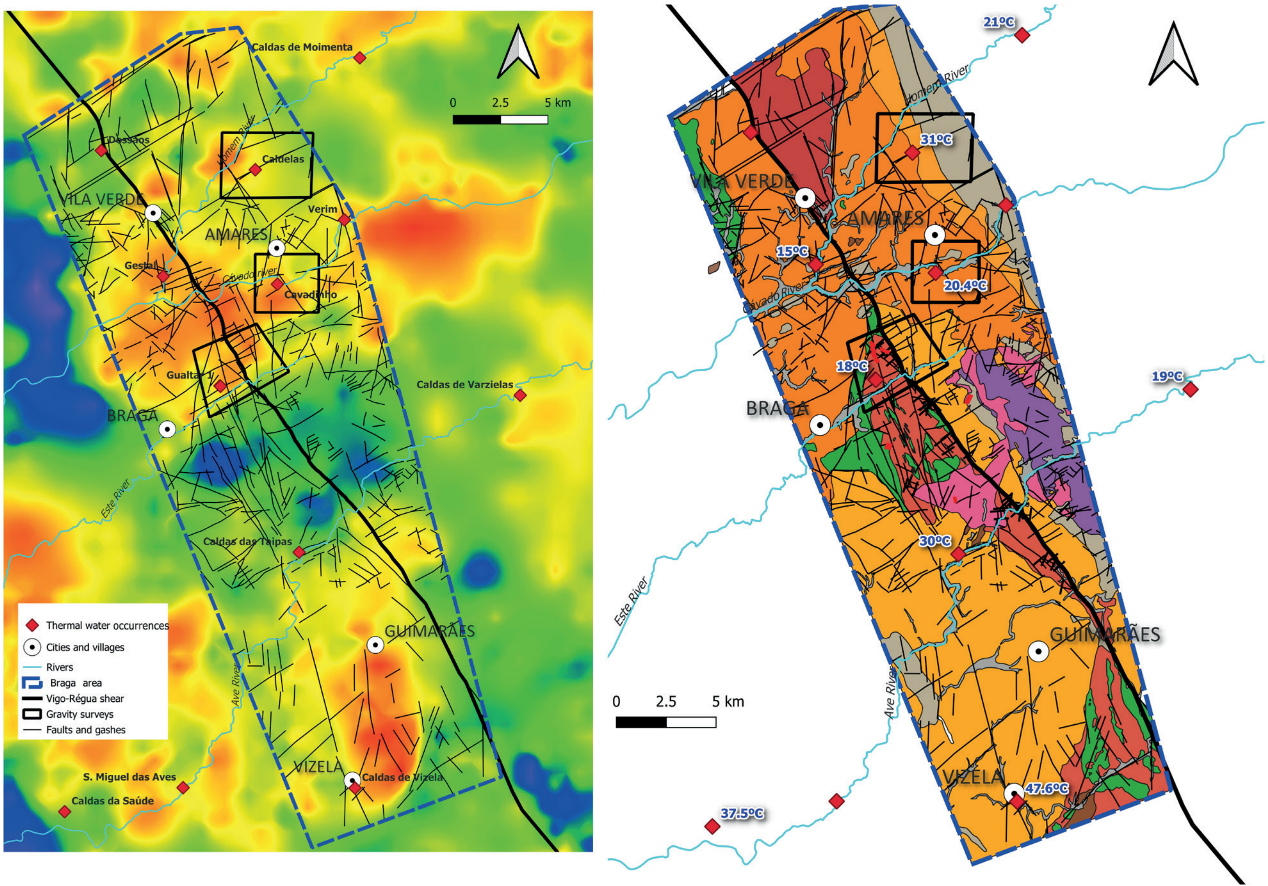

Figure 8: Comparison between radiometric and geological background from the study area and study sites.

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Municipality of Cestica, North-western Croatia: Techno-economic analysis of investment in geothermal energy

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The Pannonian part of Croatia is rich in geothermal water sources, while there are few mineral and thermo-mineral springs. Considering the available data, the possibilities of using geothermal energy in the municipality of Cestica, NW Croatia are investigated. Its location and distance from existing geothermal sites gives a positive and realistic assumption for the existence of low-temperature (below 100 °C) reservoirs of geothermal water in the municipality. This paper presents a techno-economic analysis that includes savings in fossil fuels and a consequent decrease in greenhouse gas emissions in the atmosphere for a low-temperature geothermal site and parameters that can justify investment in further exploration and development, and also in its contribution to the energy transition.

La partie pannonienne de la Croatie est riche en sources d'eau géothermiques, alors qu'il existe peu de sources minérales et thermo-minérales. Compte tenu des données disponibles, les possibilités d'utilisation de l'énergie géothermique dans la municipalité de Cestica, au nord-ouest de la Croatie, sont étudiées. Son emplacement et sa distance par rapport aux sites géothermiques existants donnent une hypothèse positive et réaliste de l'existence de réservoirs d'eau géothermique à basse température (inférieure à 100 °C) dans la municipalité. Cet article présente une analyse technico-économique qui inclut des économies de combustibles fossiles et une diminution conséquente des émissions de gaz à effet de serre dans l'atmosphère pour un site géothermique à basse température, ainsi que des paramètres pouvant justifier des investissements pour poursuivre les efforts d'exploration, et enfin à sa contribution à la transition énergétique.

La región de Panonia en Croacia es rica en fuentes de agua termales, aun cuando que hay pocos manantiales minerales y termo minerales. Teniendo en cuenta los datos disponibles, se investigan las posibilidades de utilizar la energía geotérmica en el municipio de Cestica, al noroeste de Croacia. Dada la ubicación y distancia de las localidades geotérmicas existentes da una suposición positiva y realista de la existencia de reservorios de agua termales de baja temperatura (por debajo de 100 °C) en el municipio. Este artículo presenta un análisis tecno económico que toma en consideración el ahorro de combustibles fósiles y la consiguiente disminución de las emisiones de gases de efecto invernadero a la atmósfera para un sitio geotérmico de baja temperatura así como parámetros que pueden justificar la inversión en exploración y desarrollo adicionales, como su contribución a la transición energética.

1. Introduction

The municipality of Cestica is in the northwestern, Pannonian part of Croatia. The area of the municipality is 46 km^2, with a population of about 6,000 people. The active population is mainly engaged in viticulture, agriculture and farming as the main economic activities. The municipality also has ambitions to develop tourism. The purpose of the feasibility study of geothermal energy use was an analysis of the profitability of the investment for further geological surveys and potential exploitation activities, in order to use geothermal water for the heating of households and greenhouses and for balneology.

The Pannonian part of Croatia is rich in geothermal water sources and the thermal waters of north-western Croatia are associated with certain tectonic and lithostratigraphic conditions. Considering the expected depths of potential geothermal water at approximately one thousand metres, according to the indicated gradients, the temperature of geothermal water in the reservoir would range from 50–60 °C, and expected usability for direct heating is 30 °C [1]. It is important to point that this location has low-temperature geothermal potential (<100 °C). This is usually not of interest to potential investors, but considering recent trends of prices of energetic resources and prices of CO_2 emissions, mostly from combustion, low-temperature reservoirs have potential to gain the attention of investors and subsequently to participate in the energy transition.

The contribution of this paper is the demonstration of geology as a basis for defining the profitability of energy projects, and emphasising the importance of economic geology and its further development with regard to new requirements.

2. Materials and Methods

This paper presents techno-economic analyses as the basis of rational research and production of geothermal energy. The following components are discussed:

1. Investments,
2. Expenditures,
3. Revenues.

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Table 1: Lithostratigraphic division of the Croatian part of the Pannonian Basin [3].

Sava Depression	*Drava Depression*	*Mura Depression*	*Slavonsko–Srijemska Depression*	*Stratigraphy unit*
Lonja Formation	*Lonja Formation*		*Vuka Formation*	*Upper and Middle Pliocene and Quaternary*
Široko Polje Formation	*Bilogora Formation*		*Vera Formation*	*Upper Pontian*
Kloštar–Ivanić Formation	*Kloštar–Ivanić Formation*	*Lendava Formation*	*Vinkovci Formation*	*Lower Pontian*
Ivanić–Grad Formation	*Ivanić–Grad Formation*			*Upper Pannonian*
Prkos Formation	*Križevci Formation*	*Murska Sobota Formation*	*Valpovo Formation*	*Lower Pannonian*
Prečec Formation	*Mosti Formation*		*Vukovar Formation*	*Pre-Badenian, Badenian, Sarmatian*
Pre-tertiary rocks, Mesozoic carbonates, Paleozoic magmatite and metamorphic complex				

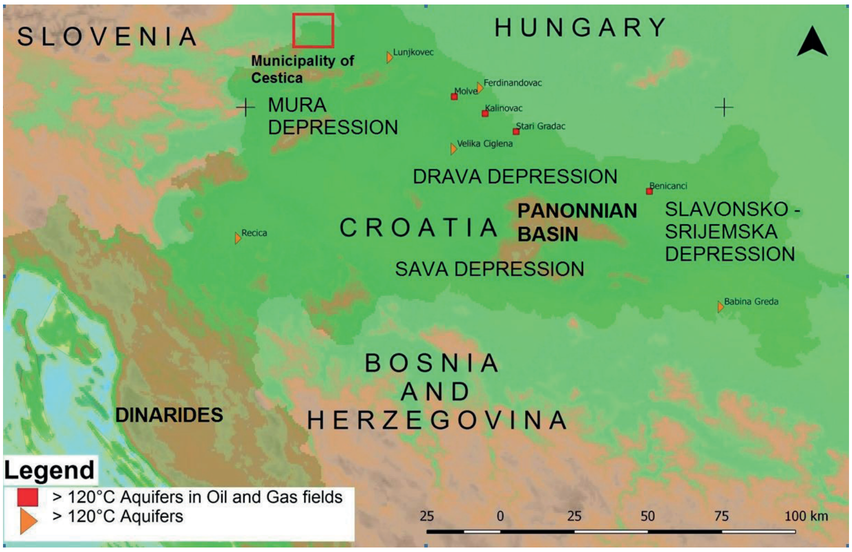

Figure 1: Project area and significant geothermic aquifers in Croatia [4, 5].

Table 2: Estimation of total planned investment [1].

Description	*EUR*
Two Boreholes – drilling, materials	*2,000,000*
Additional geological and geophysical surveys (10% of drilling costs)	*200,000*
Equipment – submersible centrifugal pump, heat exchanger, signalling and automation, connecting pipelines	*300,000*
Other	*200,000*
TOTAL	*2,700,000*

Energetic projects are long-term projects, so this evaluation was done for a period of 20 years. The prices for each component depend on the market, which is volatile, so a rough estimation for each parameter was used for estimating whether such a project is feasible or not. If there is interest in further development, the techno-economic evaluation will be upgraded with more precise parameters. Starting from the initial settings, within the territory of the municipality of Cestica the expected values of geothermal gradient are 40 °C/km and in more favourable situations well over 50 °C/km. Within the expected depths of potential geothermal reservoirs at a depth of one thousand metres, according to the indicated gradients, the temperature of geothermal water in the reservoir would range from 50–60 °C, while the expected usability for direct heating is 30 °C. Estimated inflows for the predicted type and depth of the reservoir range from a thousand to a few thousand cubic metres per day. Preliminary investment was taken from the feasibility study [1], which is based on prices of drilling and surveying for the Croatian part of the Pannonian Basin.

Data from the commodity exchange were used for prices of natural gas [6] and CO_2 [7]. Considering the volatility of commodity markets, averages of long-term prices trends were taken. For natural gas, the average price was taken for the time period 1998 – Jun 24 2022 (***Table 3***), and for CO_2, the average price was taken for the time period 2008–24 June 2022 (***Table 4***). Considering that the prices were expressed in different currencies, the relationship between currencies at the time of writing the paper was taken into account.

3. Geology

The Republic of Croatia can be roughly divided in two different areas: the Pannonian Basin and the Dinarides. In the Dinarides the average geothermal gradient is 0.018 °C/m. In the Pannonian Basin, the average geothermal gradient is much higher: 0.049 °C/m [2]. Since the geothermal gradient in the Pannonian area is considerably higher than the European average (0.043 °C/m), in addition to already discovered geothermal fields, it is probable that new fields will be discovered. The Croatian part of the Pannonian Basin is divided into four depressions: the Drava Depression, Mura Depression, Sava Depression and Slavonija-Srijem Depression. Oil and gas reservoirs along with source rocks are placed in a Neogene complex, which is divided into formations. Each depression has its own division (***Table 1***). Dominating lithology members are sandstones and marls from Lower Pannonian to Upper Pontian, which overlay eroded rocks of a pre-Ter-

Table 3: Historical annual average prices of natural gas (USD/MMbtu). Data from Henry Hub Natural Gas Spot Price - Historical Annual Data [6].

Year	Price USD per MMbtu	Price EUR per MMbtu (1 USD = 0.95 EUR)
1998	2.09 USD	1.99 EUR
1999	2.27 USD	2.16 EUR
2000	4.31 USD	4.09 EUR
2001	3.96 USD	3.76 EUR
2002	3.38 USD	3.21 EUR
2003	5.47 USD	5.20 EUR
2004	5.89 USD	5.60 EUR
2005	8.69 USD	8.26 EUR
2006	6.73 USD	6.39 EUR
2007	6.97 USD	6.62 EUR
2008	8.86 USD	8.42 EUR
2009	3.94 USD	3.74 EUR
2010	4.37 USD	4.15 EUR
2011	4.00 USD	3.80 EUR
2012	2.75 USD	2.61 EUR
2013	3.73 USD	3.54 EUR
2014	4.37 USD	4.15 EUR
2015	2.62 USD	2.49 EUR
2016	2.52 USD	2.39 EUR
2017	2.99 USD	2.84 EUR
2018	3.15 USD	2.99 EUR
2019	2.56 USD	2.43 EUR
2020	2.03 USD	1.93 EUR
2021	3.89 USD	3.70 EUR
2022	6.01 USD	5.71 EUR[1]
AVERAGE:	4.30 USD	4.09 EUR

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[1] Averaged data up to 24 June 2022

Table 4: Historical annual average prices of CO_2 (EUR/tonne). Data from Carbon Emissions Futures Historical Data [7].

Year	EUR
2008	21.40 EUR
2009	13.15 EUR
2010	16.31 EUR
2011	19.02 EUR
2012	7.61 EUR
2013	4.49 EUR
2014	5.97 EUR
2015	7.68 EUR
2016	5.35 EUR
2017	6.22 EUR
2018	17.51 EUR
2019	26.08 EUR
2020	25.45 EUR
2021	54.01 EUR
2022	83.44 EUR[1]
AVERAGE:	20.91 EUR

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[1] Averaged data up to 24 June 2022.

tiary complex. The municipality of Cestica is located in the Croatian part of the Pannonian Basin in the Mura Depression (***Figure 1***). In the area of the municipality of Cestica, expected geothermal reservoirs are located in pre-Tertiary fractured rocks at easily accessible depths (at roughly 1000 to 1200 m below the surface). The drilling target is at depths of about 1000–1200 m and expected temperatures at these intervals range between 50 and 60 °C [1].

4. Results of Techno-economic analysis

4.1. Investments

Estimated investments amount to approximately EUR 2.7 million (***Table 2***), and consist of:

1. Investment in the construction of two wells (extraction and injection), each 1000–1200 m deep;
2. Investments in necessary underground and surface equipment.

4.2. Expenditures

The production of geothermal water is burdened by costs and obligations estimated according to the amount of water produced and consist of:

- Electricity consumption,
- Maintenance of well equipment and systems for preparation of geothermal water for use,
- Compensation for the exploitation of geothermal water.

Expenditures are estimated to total approximately EUR 30,000.

4.3. Revenues

Table 3 presents the calculation of thermal power for the forecasted amount of geothermal water production of 1000 m^3 per day, which is a realistic amount considering the expected parameters of the reservoir and with production from a deep centrifugal pump. Revenues are thus calculated for the production of 1000 m^3 of geothermal water per day and for expected usability of geothermal water temperature of 30 °C.

Comparing the energy value of geothermal water and natural gas, it is prominent that 1 m^3 of geothermal water at a temperature of 30 °C give an energy value equivalent to 3.3 Sm^3 of natural gas [1]. In calculating total revenue, the average price of natural gas from 1998 to 24 June 2022 was taken (***Table 3***).

Another important issue is the prevention of CO_2 emissions and cost savings. In calculating total revenue, the average price of CO_2 since 2008 to 2022 was taken (***Table 4***).

The price of 1 m^3 of natural gas equivalent was taken. It is important to see whether the consumpation of geothermal energy, for which we need to conduct surveys with the ever-present mining risk, will be economically competitive against natural gas.

The annual energy value of 1000 m^3 of thermal water in EUR from ***Table 5*** represents the annual revenue parameter. The value of the annual revenue parameter was rounded down to EUR 231,000, which increases the level of security of the revenue calculation (***Table 6***).

According to the energy institute Hrvoje Požar [8], the average natural gas energy consumption for a five-year period (2015–2020) in Croatia was 97,776.67 TJ of natural gas per year, and the annual average value per capita was 0.024224 TJ of natural gas. For the 6000 inhabitants in the Cestica municipality this means 145.344 TJ annually.

Other fuels used primarily for heating are coal and biomass from wood. The average annual coal energy consumption for the same five-year period (2015–2020) was 23,838.33 TJ, and the annual average value per capita was 0.0059 TJ of coal; for the 6,000 inhabitants in the Cestica municipality this means 35.435 TJ annually. The average annual energy consumption from wood for the five-year period was 53,435 TJ, or 0.013 TJ of wood annually per capita; for the Cestica municipality this means 79.43 TJ annually.

The total consumption of energy for 6000 inhabitants is:

$$E_{total} = E_{natural\ gas} + E_{coal} + E_{wood} = 145.34\ \text{TJ} + 35.44\ \text{TJ} + 79.43\ \text{TJ} = 260.21\ \text{TJ}.$$

1000 m^3 of thermal water can ensure 45.81 TJ, which is 31.52% of the energy consumption from natural gas or 17.61 % of the total energy consumption for heat ($E_{natural\ gas} + E_{coal} + E_{wood}$).

Table 5: Energy ratio between geothermal water and natural gas.

Item	***Quantity***	***Unit***
Volume of geothermal water for a day	*1,000*	*m^3/day*
Volume of geothermal water for a year	*365,000*	*m^3/year*
Energy for a day at usability temperature of 30 °C	*30,000,000*	*kcal/day*
125,520,000	*KJ/day*	
Energyfor a year at usability temperature of 30 °C	*10,950000,000*	*kcal/year*
45814,800,000	*KJ/year*	
45.81	*TJ/year*	
Equivalent energy of natural gas for a year in MMbtu	*43,424.05*	*MMbtu/year*
Price of natural gas in euro (MMbtu)	*4.09*	*EUR/MMbtu*
Price of natural gas in euro annual	*177,604.36*	*EUR/year*
Emission factor tCO_2 / TJ (Terajoule)	*56.10*	*tCO_2/TJ*
Total Emission tCO_2 / in a year	*2,569.941*	*tCO_2/year*
Price per emission unit in euro	*20.91*	*EUR/tCO_2*
Annual Emission Fee	*53,737.47*	*EUR/ year*
Annual expense of Natural gas annual + Annual Emisson Fee	*231,341.83*	*EUR/ year*

Table 6: Preliminary estimation of total planned investment revenue for the production of 1000 m^3/day of thermal water.

Year	***Revenues***	***Investment***	***Expenditure***	***Revenues cumulative***	***Investments+Expenditure cumulative***	***Net profit***
	EUR	***EUR***	***EUR***	***EUR***	***EUR***	***EUR***
1	*231,000*	*2,700,000*	*30,000*	*231,000*	*2,730,000*	*-2,499,000*
2	*231,000*	*0*	*30,000*	*462,000*	*2,760,000*	*-2,298,000*
3	*231,000*	*0*	*30,000*	*693,000*	*2,790,000*	*-2,097,000*
4	*231,000*	*0*	*30,000*	*924,000*	*2,820,000*	*-1,896,000*
5	*231,000*	*0*	*30,000*	*1,155,000*	*2,850,000*	*-1,695,000*
6	*231,000*	*0*	*30,000*	*1,386,000*	*2,880,000*	*-1,494,000*
7	*231,000*	*0*	*30,000*	*1,617,000*	*2,910,000*	*-1,293,000*
8	*231,000*	*0*	*30,000*	*1,848,000*	*2,940,000*	*-1,092,000*
9	*231,000*	*0*	*30,000*	*2,079,000*	*2,970,000*	*-891,000*
10	*231,000*	*0*	*30,000*	*2,310,000*	*3,000,000*	*-690,000*
11	*231,000*	*0*	*30,000*	*2,541,000*	*3,030,000*	*-489,000*
12	*231,000*	*0*	*30,000*	*2,772,000*	*3,060,000*	*-288,000*
13	*231,000*	*0*	*30,000*	*3,003,000*	*3,090,000*	*-87,000*
14	*231,000*	*0*	*30,000*	*3,234,000*	*3,120,000*	*114,000*
15	*231,000*	*0*	*30,000*	*3,465,000*	*3,150,000*	*315,000*
16	*231,000*	*0*	*30,000*	*3,696,000*	*3,180,000*	*516,000*
17	*231,000*	*0*	*30,000*	*3,927,000*	*3,210,000*	*717,000*
18	*231,000*	*0*	*30,000*	*4,158,000*	*3,240,000*	*918,000*
19	*231,000*	*0*	*30,000*	*4,389,000*	*3,270,000*	*1,119,000*
20	*231,000*	*0*	*30,000*	*4,620,000*	*3,300,000*	*1,320,000*
Total	*4,620,000*	*2,700,000*	*600,000*			
Profit			*1,320,000*			

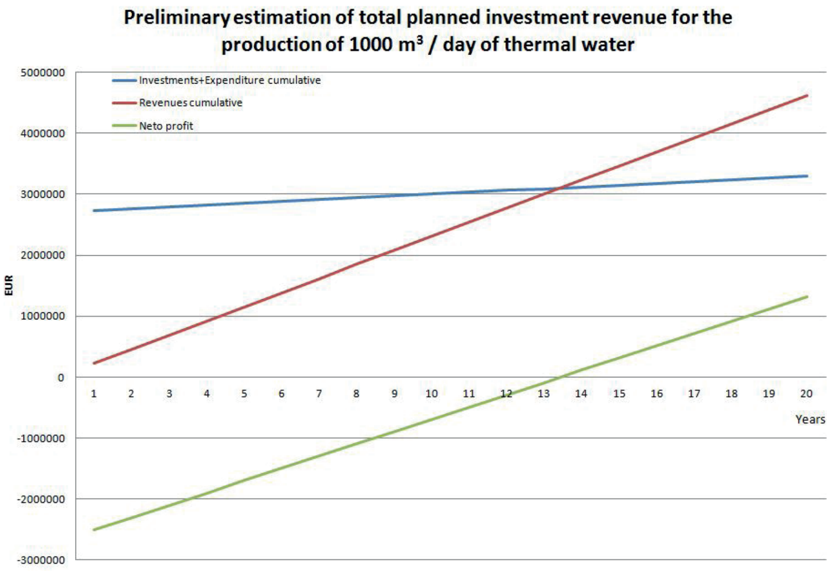

Figure 2: Preliminary estimation of total planned investment revenue for the production of 1000 m3/ day of thermal water – graphic display.

According to the preliminary estimation of revenue, the daily production of 1000 m^3 of thermal water will lead to a return on investment after thirteen years, with expected profit of EUR 1,320,000 after 20 years of operation.

Daily production of 1000 m^3 of thermal water represents a relatively small amount, which still covers 31.52% of the energy consumption from natural gas or 17.61 % of the total energy consumption for heat. The pumping rate can be significantly increased without a significant increase in expenses, which can return the investment earlier.

This energy calculation and economic-financial assessment of profitability is burdened by mining risk, which will be minimised by further surveys and more detailed study. The big problem with geothermal energy is that it cannot be transported over long distances; it must be used in an environment close to the well.

The programme of economic use of geothermal energy will be designed according to the possible volume of production after the construction of the well. It is launched to achieve beneficial economic and social effects for the local and wider community through increasing tourist attractions with thermal baths and for use in greenhouse production.

These techno-economic indicators can attract potential investors because of geothermal energy's reputation as a safe, environmentally friendly energy souce that is cheaper than other sources of energy. The fact is that after the return on investment, geothermal energy is certainly the cheapest energy source, burdened only with production costs.

5. Discussion

This paper presents a plan for use of geothermal energy as an internal heating source for households, greenhouses and for balneology, which can contribute to further development of tourism and recreation. Once experience is gained at the first site, it is possible to extend the user network and to raise interest in further investment in this area.

5.1. Contribution to the energy transition and a low-carbon economy

According to the preliminary estimation of daily production, 1000 m^3 of thermal water provides 34,890 kWH (34.89 MWh) of thermal energy per day, or 12,734.85 MWh of produced thermal energy per year, which means savings of the equivalent energy of natural gas.

Rising energy prices and supply instability have led to serious increase in interest in developing geothermal resources and have triggered a completely new way of understanding country's geothermal potential [9]. The average energy capacity of geothermal direct heat consumption in Croatia is 3–4 MWt and it is expected that there is another 1,500 to 2,000 MWt, which could generate as much heat as 600 million m^3 of natural gas per year [9].

Each terajoule obtained by combustion of methane emits 54.9 tonnes of CO$_2$, which means the emission factor of methane is 54.9 tCO$_2$/TJ [10]. Expected daily produced thermal energy is 34.89 MWh, or 0.13 TJ, which means a decrease in greenhouse gas emissions by 7.14 tCO$_2$/day, or 2,606 tCO$_2$/year. These annual emissions of CO$_2$ are relatively low; for example, installations for fuel combustion with low emissions can emit up to 25,000 tCO$_2$/year [10], but further experience is expected to enable development of further capacities in the future.

5.2. Anticipation of additional surveys

In addition to establishing the framework of feasibility of the overall project, the techno-economic evaluation should be kept in mind at each step in the project, so a further step is deciding on the type and scope of the survey.

According to general geological situation in the surrounding area, it can be concluded that this area has a great deal of potential, but this assessment needs direct confirmation. It can be directly confirmed by drilling an exploration well that can be used for production in the case of positive results. Drilling requires the activation of significant material and financial resources, so each exploration and production well carries geological and technological risk, which can jeopardize the whole project.

In order to decrease geological and technological risk, it is necessary to have an idea of the rational scope of investment in indirect geological and geophysical surveys for risk reduction. The risk cannot be completely eliminated, and for some risks there is no indirect survey methodology for defining them. In practice, the rational level of funds for a geological survey is one tenth of the value of the construction of the exploration and injection well (Table 2). Invested amounts in geological and geophysical surveys can cover a significant scope of geophysical surveying methods, such as geoelectric, magnetic and telluric methods, and with analysis of detailed geological, hydrogeological and geochemical indications.

These methods can be efficient in combination with existing data, but the final decision on the scope of surveys should be taken by the investor(s).

6. Conclusion

In this paper the expected properties of a low-temperature (<100 °C) geothermal water deposit were calculated. The original study was performed in 2011 for the Cestica municipality in the Pannonian section of Croatia. Considering the relatively low price of natural gas at that time, combined with the low price of greenhouse gas emissions and not completely established ETS, the feasibility of this project was positive, but with small revenue compared to the initial investment. The trend of increasing energy prices in combination with the established ETS system and rising CO_2 emission prices have made projects of this type more attractive to investors in recent years.

It is clear that high-temperature geothermal deposits will always be more attractive to investors due to greater investment return possibilities, such as the possibilities of electricity production and of supplying a wider network of consumers, but the current trend of rising energy prices has increased the potential profitability of low-temperature geothermal reservoirs.

The advantage of low-temperature thermal reservoirs is their availability and wide distribution. The techno-econoic analysis reported here was done for a period of 20 years, which is a common practice for energetic facilities, in comparison with 20-year averages of gas prices and CO_2 emission unit prices. Considering expected long-term trends (energy demands, spreading of the ETS), the prices will almost certainly remain high. A conservative approach was used, with a low pumping rate used in the calculation for the minimum value, and thus there is a prospect for significant increase if higher pumping rates are feasible. The complete return on investment is expected in the third quarter of the considered period, around year 13 or 14, and after that it is expected to bring a profit.

Despite the fact that this is only a preliminary assessment, it is evident that in the future projects of this type will be of interest to investors, especially from the aspect of energy transition requirements.

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Conflicts of Interest: The author declares no conflict of interest.

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Exploring low enthalpy geothermal energy in Costa Rica: A pilot project to improve tourism energy matrix efficiency

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Geothermal energy has been an important and stable part of the renewal energy matrix of Costa Rica for more than 25 years. However, the exploitation has been centred in high enthalpy energy for electric power generation, relegating the low enthalpy range to touristic uses like thermal spas. This pilot project is pioneering in the country, aiming to improve the energy efficiency of a local thermal resort by directly using the geothermal resource available. First, a geochemical and geological characterization of hydrothermal wells, springs and surrounding river was done to study local geothermal potential. Based on local geothermal capacity, direct-use engineering applications of low enthalpy geothermal resource were proposed to meet some energetic necessities of the hotel and enhance its efficiency.

L'énergie géothermique est une partie importante et stable de la matrice d'énergie renouvelable du Costa Rica depuis plus de 25 ans. Cependant, l'exploitation s'est concentrée sur l'énergie à haute enthalpie pour la production d'énergie électrique, reléguant la gamme à basse enthalpie à des usages touristiques comme les thermes. Ce projet pilote est pionnier dans le pays, car il vise à améliorer l'efficacité énergétique d'une station thermale locale en utilisant directement la ressource géothermique disponible. Premièrement, une caractérisation géochimique et géologique des puits hydrothermaux, des sources et de la rivière environnante a été réalisée pour étudier le potentiel géothermique local. Sur la base de la capacité géothermique locale, des applications d'ingénierie à utilisation directe des ressources géothermiques à faible enthalpie ont été proposées pour répondre à certains besoins énergétiques de l'hôtel et améliorer son efficacité.

La energía geotérmica ha sido una parte importante y estable de la matriz energética renovable de Costa Rica por más de 25 años. Sin embargo, la explotación se ha centrado en la energía de alta entalpía para producción eléctrica, relegando en el rango de baja entalpía a usos turísticos como balnearios termales. Este proyecto piloto es pionero en el país, y pretende mejorar la eficiencia energética de un hotel local mediante usos directos del recurso geotérmico disponible. Primero, se hizo una caracterización de los pozos hidrotermales, manantiales y del río circundante para estudiar el potencial geotérmico local. Basados en la capacidad geotermal, se proponen aplicaciones de uso directo de la geotermia de baja entalpía, cubriendo algunas de las necesidades energéticas del hotel, y mejorando su eficiencia.

1. Introduction

Geothermal energy systems are considered hydrothermal convection systems and can be classified according to temperature into high, medium, or low enthalpy resources. High enthalpy systems have high pressure and temperature above 150 °C. These systems are commonly used for electric power generation, and their study began worldwide after the 1970s crisis [1]. Medium enthalpy systems are between 100-150 °C, whilst low enthalpy ones are below 100 °C. These systems are the most abundant and are located at shallower depths, thus resulting in great potential to develop direct-use technology. Different applications of low and medium enthalpy systems have been studied worldwide and include aquaculture, balneology, cattle breeding, urban heating, domestic water, greenhouses, fish farming, spas and resorts, and growing vegetables and treating wood products, among others [2]. Currently, the touristic sector of different countries benefits from direct uses of low-enthalpy energy, although the Central American region is still behind compared to them, mostly because of the lack of knowledge of appropriate technologies or the absence of a legal framework to implement it.

Lund *et al.* [3] show the annual energy consumption (TJ/yr) of direct uses of geothermal energy in multiple countries including Costa Rica, with data recorded between 1995 and 2020. The data indicate an important growth between 2015–2019 (52%) in the installed capacity for direct uses of geothermal energy, increasing 7% compared to the previous period (45% from 2010 to 2014). From all possible applications described by Lindal [4], and depending on each regional context, several applications have been particularly successful and have shown larger growth in the last two decades. ***Figure 1*** shows the

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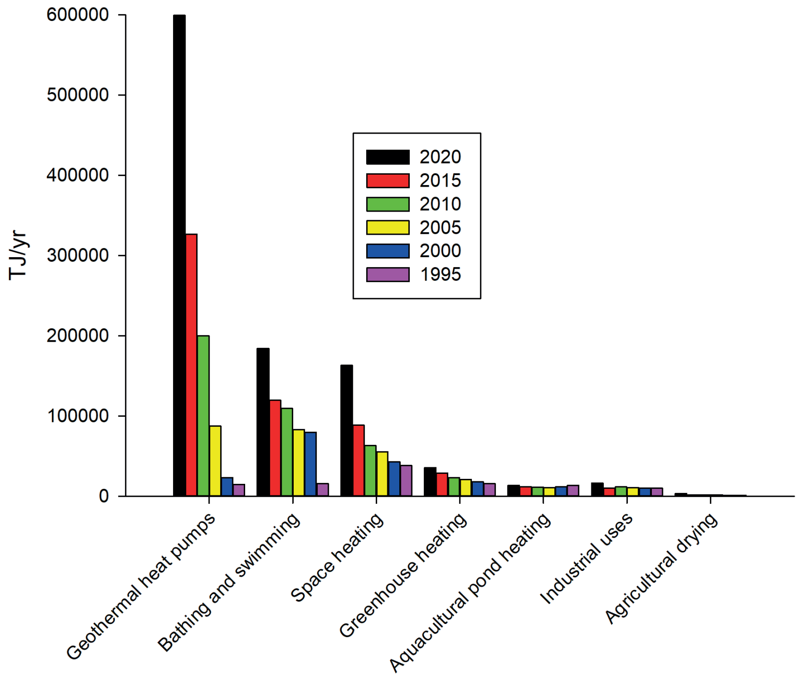

Figure 1: Comparison of worldwide direct use of geothermal energy in TJ/yr from 1995, 2000, 2005, 2010, 2015 and 2020. From Lund and Toth [5].

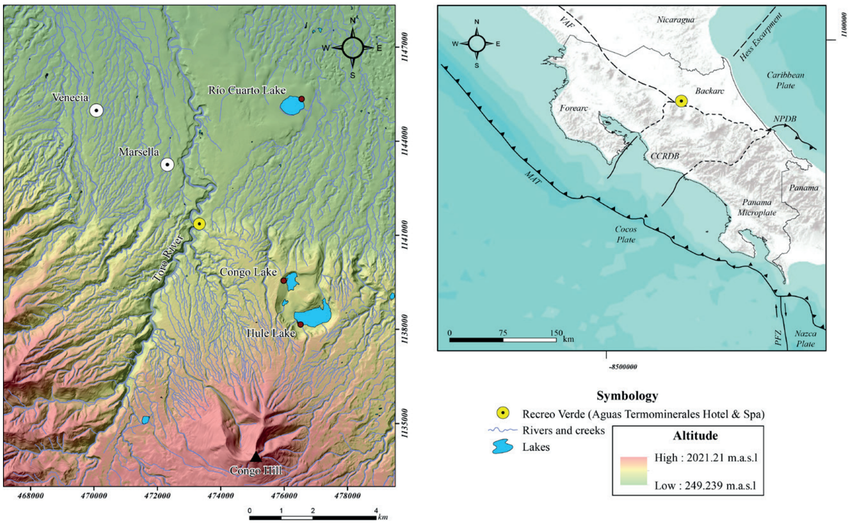

Figure 2: Location of the study site of Recreo Verde hotel in Costa Rica.

most important applications: geothermal heat pumps, bathing and swimming, space heating, greenhouse heating, aquaculture pond heating and industrial uses, with geothermal heat pumps having the largest growth, from 125,000 TJ/yr between 2010–2015 and 273,133 TJ/yr between 2012–2020 [5].

Costa Rica is the second smallest country in Central America but has great geothermal potential due to the local geotectonic environment, resulting in a sustainable and environmentally low-impact source of autochthonous energy. In the 1970s, in response to the world energetic crisis, the Instituto Costarricense de Electricidad (ICE; Costa Rican Institute of Electricity) promoted geothermal exploration in areas of potential interest that were previously highlighted by United Nations experts. This first effort covered 500 km^2, and included basal superficial exploration using geological, geochemical, and geophysical methods [6]. Currently, Costa Rica has several potential geothermal areas dispersed along the central range of the country, although the most important are in the north-western part of the Guanacaste Province, where two geothermal projects are operating and producing electric power at present. These areas exploit high enthalpy hydrothermal systems and generate around 13% of the Costa Rican energy matrix [7], placing the country as the leader in Central America and third within the American continent in geothermal capacity installed.

The entire geothermal energy potential of Costa Rica has not been explored, low-enthalpy areas are yet to be exploited and the applications are yet to be implemented. The applications of direct uses of geothermal energy in Costa Rica represent 21 TJ/yr, less than half of other countries in the Central American region such as Guatemala and El Salvador with 56 TJ/yr [3]. The low-enthalpy geothermal resource is normally found within tourism facilities across the country, where the local hydrothermal resource is mainly used for spas and balneology, evidencing the scarce development of other direct-use applications.

Thus, here we hypothesise that local low-enthalpy geothermal resources can be used to cope with the energetic necessities of a small tourism industry in Costa Rica. With this research we aim to improve the energy efficiency of a local thermal resort by directly using the geothermal resource available there. To achieve this, we first explored the geothermal potential within the hotel complex with a comprehensive multidisciplinary approach, considering the geology, geochemistry and microbiology of groundwater and superficial water resources. Then, we propose a pilot project with potential engineering solutions according to the resort's specific necessities and the characteristics of local water sources. This pilot project will set the foundations for the exploration of low-enthalpy geothermal resources and will pioneer the development of appropriate technology to maximise the potential of this energetic resource.

2. Materials and Methods

Surface and groundwater sampling was performed to establish the predominant geochemical conditions to build a conceptual hydrogeological and geothermic model that will support the selection of geothermal industrial water uses. Mineral depositions in the hydrothermal water pipeline system were sampled, too. Also, due to the social importance of the geothermal resource for tourism, a microbiological profile of hot springs was obtained, including public health indicators (faecal coliforms or FC, total coliforms or TC, *Escherichia coli* or EC and coliphages), pathogen detection (*Pseudomonas aeruginosa* or PA, *Enterococcus faecalis* or EF) and the aerobic plate microbial count (APMC).

2.1. Geological and hydrogeochemical context

The study area is in the district of Venecia, San Carlos, in the Alajuela province, in the community of Marsella, specifically in Recreo Verde Hot Springs & Spa. The site is located about 5 km to the SE of the town of Marsella, on the left side bank of the Toro Amarillo River and to the NW of Hule Lake (***Figure 2***). Regionally, the area of interest is in the northern section of the Central Volcanic Mountain ridge of Costa Rica, to the north of the Poás Volcano, which is an active stratovolcano.

The present study focuses on a local scale, where understanding the geological and groundwater chemical conditions of Recreo Verde hotel property and surrounding areas is imperative to assess the local low enthalpy geothermal energy potential. According to Ruiz *et al.* [8] the following geological formations can be found in the area (***Figure 3***):

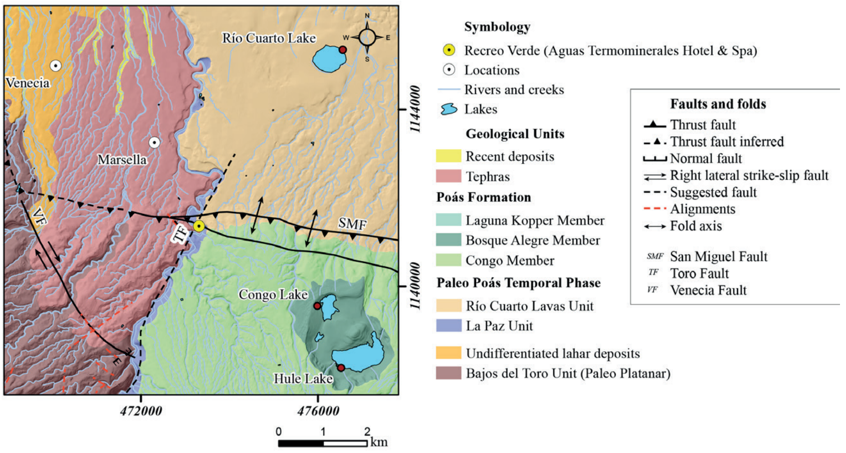

Figure 3: Geological structures near the study site of Recreo Verde hotel.

Table 1: Summary of the locations sampled within the Recreo Verde hotel property.

Sample	***Water resource type***	***Latitude***	***Longitude***
MAN-2	*Cold Spring*	*10°19′24.0″N*	*84°14′49.6″W*
P2-2	*Hydrothermal well*	*10°19′17.6″N*	*84°14′34.1″W*
P3-2	*Hydrothermal well*	*10°19′13.4″N*	*84°14′37.8″W*
R-1	*Horizontal transect, point 1, Toro River*	*10°19′18.5″N*	*84°14′35.0″W*
R-2	*Horizontal transect, point 2, Toro River*	*10°19′18.7″N*	*84°14′35.8″W*
R-3	*Horizontal transect, point 3, Toro River*	*10°19′19.3″N*	*84°14′35.5″W*

1. Temporal phase Paleo Poás: Río Cuarto lavas unit (201 ± 30ka), is composed of basaltic andesitic lava flows and underlays the Congo Member. The origin is related to volcanic focus of the Late Paleo Poás phase or Early Neo Poás.
2. Congo Member (35.6 ± 0.6 ka): this belongs to the Poás Formation and is composed of kalco alkaline basalts to andesites with low to normal K content, these lava flows are covered by pyroclastic deposits. This geological member has an age of Late Pleistocene.
3. Bosque Alegre (6.1 ka): this is composed of pyroclastics and a few basalts with olivine lava flows; these materials were produced by Hule maar.
4. Laguna Kooper Unit (3-4 ka): these materials were grouped in three layers of pyroclastic deposits, associated with Río Cuarto o Kopper maar.
5. Fluvial deposits and tephras: this is one of the youngest geological deposits in the area, belonging to distal phases of Congo and foothill deposits of the San Miguel escarpment.

Alvarado and Carr [9] indicate that different geochemical and geothermal studies have resulted in a high potential for geothermal energy in areas surrounding the study site; the authors highlight the hot springs of La Marina, the Toro River valley and the extinct fumarolic area of Cerro Viejo, which have several fault systems with NNW-SSE, NNE-SSW and NE-SW directions.

The Platanar-Porvenir volcanic complex is associated with a regional thermic anomaly controlled by deep geological structures [10]. This complex was classified as an A1 reservoir with an optimal vocation for heating extraction, presenting temperatures above 200 °C at three kilometres depth. This report also mentions the existence of manifestations of thermal waters in the N sector of Cerro Congo, characterised by low temperatures, moderate conductivity, and neutral pH, as well as being mostly Bicarbonate-alkaline-type with a lesser extent as Chloride-sodium type.

Soto [11] indicates that there are emanations of thermal waters along the trace of the San Miguel fault, as well as small fractures with CO_2 emanations. Also, in the vicinity of the Hotel Recreo Verde, near the Toro III Hydroelectric Project, ICE [12] identified a faulting pattern with a NW-SE and N-S direction, the product of local effects associated with the activity of the Poás Volcano and regional strengths due to the subduction process. Moreover, Vargas [13] studied and classified the nearby Poco Sol Geothermal Field as a liquid dominant high temperature geothermal field and pointed it out as one of the most promising geothermal prospects in Costa Rica.

ICE [14] carried out a series of hydrogeochemical analyses upstream and downstream the Toro Amarillo River and its main tributaries, as well as in hot springs located on both banks of the Toro Amarillo River, especially in hot springs located in the vicinity of the Recreo Verde Hotel. As a result of this study, hot springs were classified as hyperthermal due to their temperature, and as practically neutral magnesium bicarbonate waters, associated with the dissolution of CO_2 in the water at greater depths. In terms of the hydrogeological conditions, this highlights that most of the thermal springs are associated with perched aquifers facilitated by the highly permeable geological materials, especially the Congo Distal and Bajo del Toro Units.

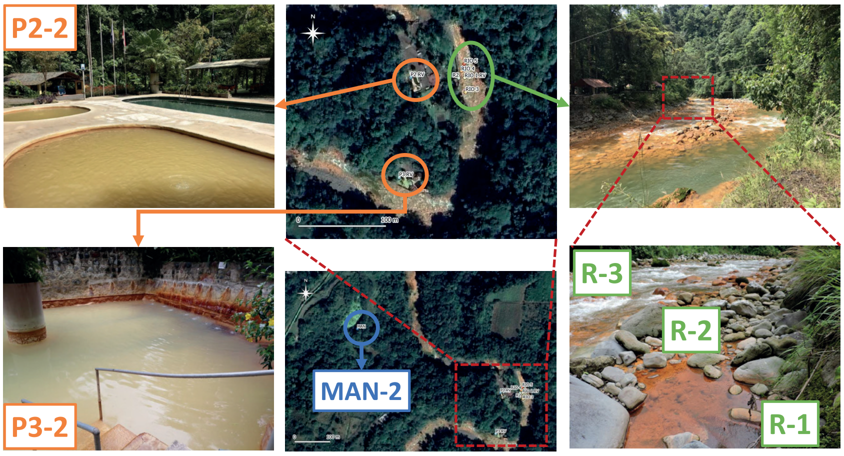

Figure 4: Geographical distribution of the six locations sampled within the Recreo Verde hotel property (see labels and details in Table 1; bottom right-hand photo is reversed from upper photo reference).

The study also indicates that the hot springs located in this sector tend to be pH neutral. In addition, it is mentioned that the deep reservoir presents temperatures between 282 and 295 °C, and that there is the presence of two aquifers, one confined and one superior, the first presenting slightly alkaline waters and the second slightly acidic [14].

ICE [14] determined the presence of several geological structures (***Figure 3***), that included the NW, W and SW sectors of the study area. As part of the field work carried out, the presence of the San Miguel inverse fault was corroborated, characterised by having an escarpment in the N72°W direction. In addition, the study determined a series of alignments parallel to the trace of the San Miguel fault, with dextral displacement components, as well as the presence of the Toro fault, which has a sinistral displacement component and is indicated by the alignment of the Toro Amarillo River in a NE direction, running through a boxed channel. Finally, downstream of the main intake, at the Hotel Recreo Verde, there is a system of inverse faults trending NE, parallel to the Toro fault [14].

2.2. Location and geochemical sampling

Samples were collected in Recreo Verde Hot Springs & Spa in Marsella, San Carlos, Costa Rica, during the rainy seasons of 2020 (October) and 2021 (June). Sample locations considered two hydrothermal wells, one spring water well and surface water from three points at the north margin of the Toro River that surrounds the resort property (***Table 1, Figure 4***). Those river points were sampled considering a horizontal transect starting at the boundary of the river next to the hotel property limit (R-1), where an area of hydrothermal discharge seemed to be present. A sample was collected every 3 m from this point towards the inner section of the river (R-3) (***Figure 4***).

Water samples were collected from each location to analyse water geochemistry, dissolved gases and microbial composition. Rinsed bottles were used to collect water samples, tedlar bags to sample gases and sterile recipients to analyse microorganisms. Major cations (ICP-AES), minor cations (ICP-MS) and principal anions were analysed at Bureau Veritas laboratory, Canada.

Field parameters were also measured at each sampling site using a multiparameter probe (Hannah Instruments, HI9829): temperature, pH, ORP, dissolved oxygen, conductivity, total dissolved solids, turbidity and resistivity. Additional points of the northern margin of the river surrounding the hotel facilities were analysed for physicochemical parameters, too.

Mineral depositions within the thermal water pipeline of the hotel were sampled. The minerals were analysed by X-ray diffraction spectroscopy (XRD, PANanalytical Empyrean, analysed at the Instituto Tecnológico de Costa Rica), Fourier-transform infrared spectroscopy (FTIR,

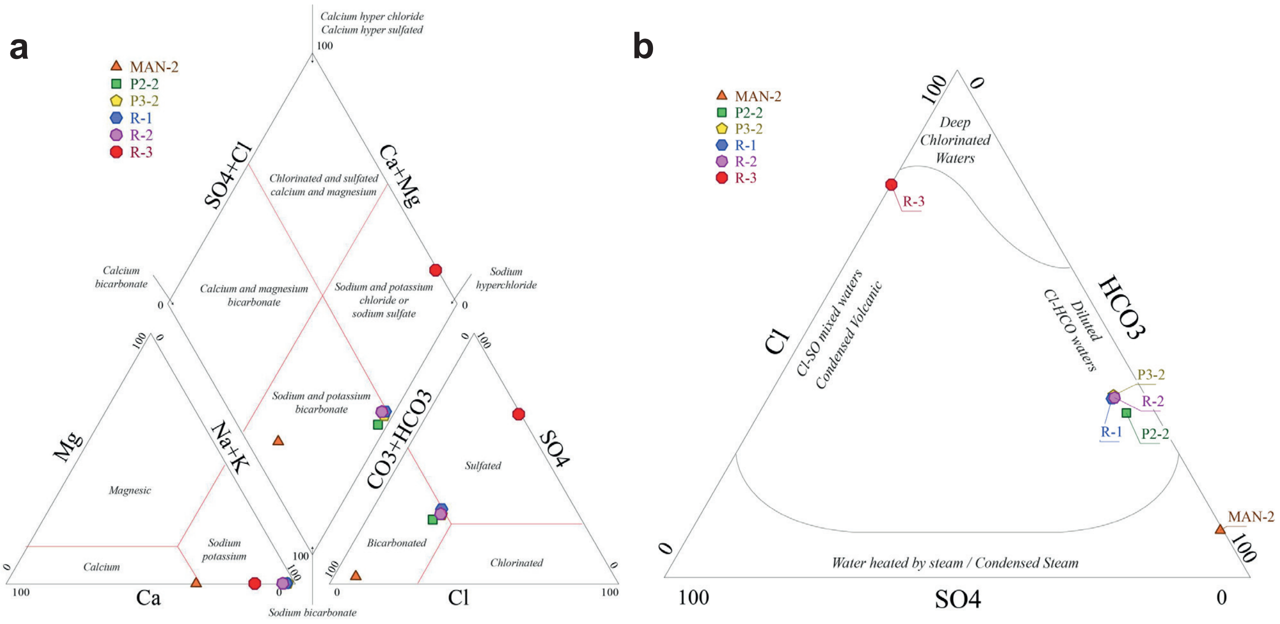

Figure 5: Water geochemistry results for the six locations sampled within the hotel property: (a) Piper diagram and (b) ternary graph. Details of concentrations can be found in the supplementary material.

Table 2: Field parameters measured in each water source of the six sampling locations within the hotel property.

Sample	T (°C)	pH	ORP (mV)	OD (ppm)	DO (%)	Conductivity (mS/cm)	SDT (ppm)	Salinity (PSU)
MAN-2	22.99	7.66	221.3	4.29	51.4	0.147	73	0.07
P2-2	38.64	7.13	-6.8	0.77	13.3	4.945	2453	2.51
P3-2	43.27	7.27	-58.2	1.12	18.1	6.325	3150	3.34
R-1	36.5	7.05	49.6	1.08	17.4	4.534	2264	2.37
R-2	32.16	7.07	21	2.58	40	3.016	1419	1.34
R-3	21.75	4.54	148.5	10.98	133	0.499	255	0.24

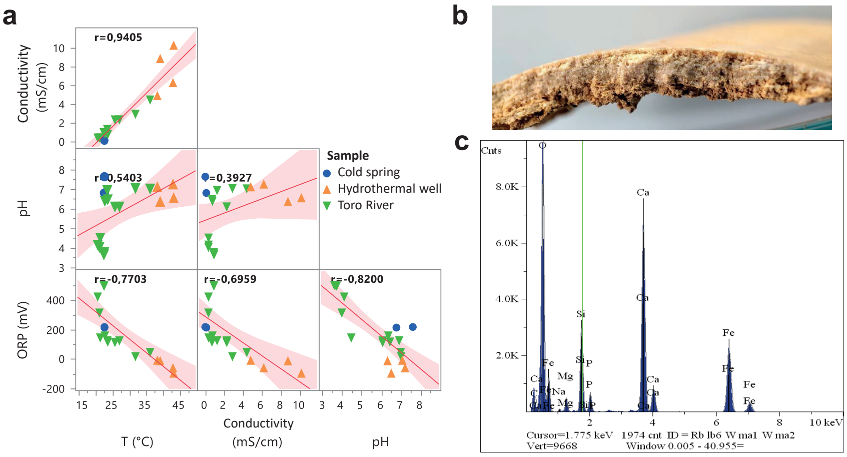

Figure 6: (a) Correlations between main field parameters measured considering all the locations from both field campaigns; (b) Transversal section of minerals deposited inside a thermal water pipeline of the hotel; (c) EDS analysis of the mineral depositions shown in (b).

Perkin Elmer Spectrum 1000) and Energy-dispersive spectroscopy (EDS, IXRF Systems) coupled to a Scanning Electron Microscope (SEM, Hitachi S-3700N).

2.3. Microbiology

Total coliforms (TC), faecal coliforms (FC) and *Enterococcus faecalis* (FC). Microorganisms were enumerated using the most probable number technique (9221E and 9230B) [15]. The sample was inoculated within less than 30 h of collection into lauryl tryptose broth (Oxoid) for TC and FC and into azide dextrose broth (Oxoid) for Enterococcus, according to APHA protocol. After an incubation period of 48 hours, tubes with a positive reaction were checked and reported.

Aerobic Plate Count (APC). APC was performed according to the pour plate method 9215B [15]. After incubation, colony forming units (CFU) were examined and counted.

Somatic coliphage quantification. With modifications, somatic coliphage concentrations were determined according to methods 9924B (somatic coliphage assay) [15]. Two hundred fifty mL of water was collected using a sterile recipient. The sample was first filtered using an 80-µm glass fiber filter (Sartorius Stedim Biotech, Goettingen, Germany) pre-treated with beef extract pH 7.2 (Oxoid) to prevent losses associated with viruses sticking to the filter. Then, a second sample filtration using 0.2 µm cellulose acetate filters (Sartorius Stedim) was pre-treated with beef extract pH 7.2. Then it was mixed with 10 ml of a fresh culture of E. coli ATCC 13706 (O.D.¼0.300 nm), $CaCl_2$, to a final concentration of 0.2 M with 2% trypticase soy agar (TSA). The mix was spread into Petri dishes and incubated at 35 °C overnight. After incubation, samples were analysed to count for plaque-forming units (PFU).

***Pseudomonas aeruginosa* (PA).** PA concentrations were detected using multiple tube techniques according to 9213F [15].

4. Results and discussion

4.1. Geochemistry and mineralogy

Samples were classified according to main ion concentration using a Piper diagram (***Figure 5a***). Two samples from Toro River (R-1 and R-2) are Bicarbonate Na-K type, as well as samples from two thermal groundwater wells (P2-2 and P3-2) located in the hotel; these waters are peripheric waters according to the Ternary graph shown in ***Figure 5b***. R-1 and R-2 were the samples from the transect closer to the hotel property (***Figure** 4*), and the water chemistry similarities found with the thermal groundwater confirmed that R-1 and R-2 were located within a discharge area of the thermal aquifer to the Toro river. Sample R–3, at the end of the transect within the Toro River, was classified as Sulphate-Na type, which is characteristic of mature waters; this sample also could be influenced by volcanic sulphur dissolution from Poás Volcano deposits. The different geochemical classification of R-3 confirmed that the geological origin of the hydrothermal groundwater found at the hotel is distinct from that of the surrounding Toro River. Geological conditions as well as the presence of some faults and alignments promote the presence of thermal groundwater at the study site. Finally, the sample from the cold spring (MAN-2) is Bicarbonate Ca water type, which corresponds to meteoric water.

The main physicochemical characteristics of the water resources in the hotel supported the geochemical differentiation of three water sources (***Figure 6a***, ***Table 2***). Thermal groundwater from wells P2 and P3 was confirmed as low-enthalpy geothermal water due to temperature range between 38-44 °C, irrespective of sampling campaigns. Additionally, these wells had low dissolved oxygen values (<2 ppm) and negative Eh values (***Table** 2*), indicating anoxic conditions. Those wells also had the highest values of TDS and conductivity (***Figure 6a, Table 2***), as was expected due to the high concentrations of dissolved cations, both major and trace elements (***Table** 3*). pH data showed circumneutral conditions for the wells in contrast to river water, where pH was close to 4. Also, R-1 and R-2, despite being in the Toro River riverbank, had values more like those measured for the thermal wells than to the last sample of the transect located inside the river (R-3) for all the field parameters measured (***Table** 2*). A similar trend can be observed with the elemental composition of the water sources

Table 3: Major cations and main minor cations analysed in each water source of the six sampling locations within the hotel property.

Sample	Al	As	B	Ba	Bi	Br	Ca	Cl
	(ppb)	(ppb)	(ppb)	(ppb)	(ppb)	(ppb)	(ppm)	(ppm)
MAN-2	<1	0.5	27	14.00	<0.05	18	12.91	2
P2-2	<600	<3000	1653	<80	<3000	*	250.0	*
P3-2	<600	<3000	1908	<80	<3000	*	75.2	*
R-1	<600	<3000	1364	<80	<3000	*	227.2	*
R-2	700	<3000	1253	<80	<3000	*	210.0	*
R-3	11939	1.0	74	14.02	<0.05	113	26.41	43

Sample	Co	Cr	Cu	Fe	K	Li	Mg	Mn
	(ppb)	(ppb)	(ppb)	(ppb)	(ppm)	(ppb)	(ppm)	(ppb)
MAN-2	<0.02	4.5	<0.1	<10	2.54	0.6	6.36	0.05
P2-2	<300	<300	<80	<10000	86	<1000	360	253
P3-2	<300	<300	<80	<10000	102	<1000	450	170
R-1	<300	<300	<80	<10000	74	<1000	311	337
R-2	<300	<300	<80	<10000	67	<1000	280	331
R-3	1.18	0.6	2.6	440	4.45	7.3	15.34	271.27

Sample	Na	Ni	P	Pb	S	Si	Sr	Zn
	(ppm)	(ppb)	(ppb)	(ppb)	(ppm)	(ppb)	(ppb)	(ppb)
MAN-2	6.85	<0.2	63	<0.2	<1	20917	122.82	0.6
P2-2	386	<300	<4000	<4000	212	*	1901	<300
P3-2	459	<300	<4000	<4000	272	*	440	<300
R-1	336	<300	<4000	<4000	194	*	1687	<300
R-2	307	<300	<4000	<4000	174	*	1584	<300
R-3	18.77	0.3	<10	<0.2	46	19453	226.02	18.6

**: not reported. / Samples with values presented as "< number" were not quantified and are presented as a value below the upper detection limit of the ICPMS. The upper limit of each element corresponds to the number after the " < " symbol. / Complete cations data can be found in the supplementary material.*

Table 4: Microbiological results of each water source of the six locations within the hotel property.

Parameter	MAN	P2	P3	Toro River
Aerobic plate count (CFU/ml)	26	1	ND	220
Total coliforms (MPN/100 m)	1.1	ND	ND	350
Faecal coliforms (MPN/ 100 ml)	ND	ND	ND	39
E. coli (MPN/ 100 ml)	ND	ND	ND	4
E. faecalis (MPN/ 100 ml)	ND	ND	ND	17
P. aeruginosa (MPN/ 100 ml)	4	ND	ND	4
Somatic coliphages (PFU/ 100 ml)	ND	100	360	ND

ND= Non detectable

(***Table 3***). These results confirmed that the points of the transect that are closer to the hotel property are within an area of hydrothermal discharge to the river.

The mineral depositions extracted from the hotel thermal water pipeline (***Figure 6b***) were confirmed as aragonite ($CaCO_3$) after XRD and FTIR analyses (***Figures S1 and S2***), as expected. However, the EDS analysis (***Figure 6c***) showed a large proportion of Fe (20–25%) within the carbonate mineralogy, even in similar proportions to calcium in some cases (20–25%), suggesting that other mineral phases such as siderite ($FeCO_3$) could be present. Si was also present but to a lesser extent (4–5%).

4.2. Microbiology and geomicrobiological potential

The microbiological parameters provided information about the quality and the presence of pathogens in the thermal spring waters. These indicators have already been referenced worldwide, given their usefulness even in identifying the source of contamination [16, 17]. Parameters such as FC, EC, and EF are useful as indicators of faecal contamination, whether of human or animal origin. They should not be naturally present in hot springs. Similarly, APMC is a general indicator of a load of aerobic microorganisms in a water sample.

Regarding ***Table 4***, most of the bacteriological parameters (FC, EC, EF) were negative or non-detectable in the water samples, which indicates there was no faecal source for contamination at the moment of sampling. Also, TC as a general guide of environmental contamination indicated a low count of total aerobic microorganisms in water samples. Note that there is no regulation in the country to establish a quantification limit in the case of thermal water.

PA is an interesting parameter to analyse in hot springs as it refers to a Gram-negative bacterium that is highly resistant to disinfection treatments and is considered a pathogen for humans. This pathogen was positive in a low concentration in the non-hydrothermal samples in this study.

Interestingly, somatic coliphages were positive in both thermal water samples (P2 and P3), with 100 and 360 PFU/100 ml. The other samples were undetectable. These are useful indicators of enteric virus contamination. Coliphages detected in wastewater reveal a significant relationship between the detection of at least one of the five human enteric viruses such are Norovirus I and II, Rotavirus, Enterovirus and Hepatitis A. Its usefulness for thermal waters could also refer to the presence of enterovirus pathogenic for humans, however, more analysis should be performed to establish an association of this parameter in hot spring waters [18].

Additionally, the anoxic and warm settings found in the hydrothermal wells

(*Table 2*), with their high concentration of metals such as iron, manganese, or sulphur (*Table 3*), suggest a potential geomicrobiological environment of interest. The biogeochemical cycles of Fe, Mn or S are well studied, highlighting crucial steps of those cycles that are developed by microorganisms via specific redox reactions, both in oxic and anoxic conditions [19, 20, 21]. Different geomicrobiological processes could be happening in these thermal environments: redox transformations of elements, biomineralisation and bioweathering of minerals; these are processes that must be further studied.

4.3. Potential uses of local low-enthalpy geothermal resource in a pilot project

Results of the geothermal potential of Recreo Verde hotel provided valuable inputs to decision- making about which direct uses can be applied at the site. Water composition, temperature and fluxes of groundwater, water springs and the surrounding river facilitated the engineering design suitable for each specific application.

The hotel is a small touristic industry, resulting in an excellent facility to implement a demonstrative pilot project to give decision-makers a starting point in the Central American region in terms of the regional low-enthalpy geothermal energy exploitation. From the study to understand the performance and the energetic necessities of the hotel, we found that several work lines can guarantee the operation of the hotel by directly using the geothermal resource and with the addition of geothermal heat pumps.

Recreo Verde hotel has 10 bungalow rooms built with a wooden structure and zinc roofing. The analysis determined that the thermal comfort of the rooms can be guaranteed using a geothermal heat pump, resulting in considerable financial savings compared to traditional acclimatising systems. Also, modifications in the rooms are recommended to avoid thermal losses and to diminish the visual impact of the future project. In terms of the heating source, the study identified local water springs that can be used as the cold focus source for the geothermal heating pump that will be using the low-enthalpy geothermal resource to the room climatization. The surrounding river can be considered as a cold focus too, but it was discarded for this purpose due to its geochemical composition and because an additional pumping system would have to be included in the final design.

Also, the hotel demands sanitary hot water for showers and for the hotel restaurant. The area has three thermal groundwater wells that can cope with this solution, but only one of them is not employed for bathing and swimming uses, so it could be exclusively used as the hot focus source for this other direct use. However, the geochemical composition of these hydrothermal systems prevents the use of that water in open circuits for heating pumps as minerals could precipitate inside the system proposed. These mineral depositions, such as the $CaCO_3$ found inside the pipelines (*Figure 6b*), could impact the effectiveness negatively or even reduce the life span of the design. Thus, a closed system design is recommended to transfer the water heat to the heating pump, and then to the accumulation reservoir that will guarantee the hot water flux according to the demand from the rooms and the restaurant.

Finally, the hotel administration is interested in producing its own food in the hotel for local consumption. The results obtained in this study and the examination of the property lead us to conclude that it is possible to design a greenhouse with an aquaponic system. The design will guarantee a circular economy system where the heat from the low-enthalpy geothermal resource will provide thermal comfort for fish and plants growing there. The system would be integrated by a geothermal heating pump for the greenhouse and a heat-exchange system for the fish farm.

Lund *et al.* [22] presents a detailed analysis of different methods to exploit the heat from low-enthalpy geothermal resources according to different applications. The proposals discussed here, based on the local geothermal potential that was determined in this study, are aligned with the applications described by Lund *et al.* [22], but some adaptations would be mandatory according to the specific site where every single application would be implemented.

5. Conclusions

Geological and structural conditions such as faults and alignments favour the presence of thermal groundwater at the study site. The geothermal resources studied are within the low-enthalpy category according to the temperature of each water sampled.

Three different water sources were identified from chemical analysis which correspond to the geological setting. Groundwater from the wells is Bicarbonate Na-K waters and in the geothermal context are peripheric waters. The cold spring receives meteoric water, and it has a characteristic HCO_3-Ca classification, while the water from the centre of the Toro River was classified as Sulphate-Na coming from deep water (mature water).

Three important applications can be implemented based on the low-enthalpy geothermal potential found, the geochemical composition of each water source in the hotel property and the operational demands of the hotel. The applications that would be developed in the pilot project are room acclimatisation, sanitary hot water supply for showers and restaurant needs, and a geothermal greenhouse coupled to an aquaponic production system. All of them will directly use the local low-enthalpy geothermal resource, thus contributing to improving the energetic matrix efficiency of the hotel. Moreover, the results of this pilot project could be replicated and expanded among the thriving Costa Rican touristic sector, contributing to the overall efficiency of renewable energy of the country.

The datasets supporting the conclusions of this article are available at ***https://doi.org/10.17632/6sh963jm64.1*** with a CC BY 4.0 license.

6. Acknowledgements

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Pathways to better integrate geothermal energy at its full technological scale in European heating and cooling networks

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Geothermal energy is a vital option to provide clean heating and cooling. Interlinking geothermal energy with the concept of heating and/or cooling networks offers excellent opportunities to benefit from economies of scale and multiplication when it comes to decarbonising the heating and cooling sector. Still, there are both technological and socio-economic challenges to foster the significant implementation of geothermal energy supplied heating and cooling networks in Europe. We identify key challenges towards better integration of geothermal energy and outline possible solutions for a boosted pan-European market uptake. Geothermal networks can only become a key technology if concepts are available to address both new and existing network infrastructures and the existing building stock.

L'énergie géothermique est une option vitale pour fournir un chauffage et un refroidissement propres. L'interconnexion de la géothermie avec le concept de réseaux de chaleur et/ou de froid offre d'excellentes opportunités pour bénéficier d'économies d'échelle et de multiplication lorsqu'il s'agit de décarboner le secteur du chauffage et du froid. Pourtant, il existe des défis à la fois technologiques et socio-économiques pour favoriser la mise en œuvre significative de réseaux de chauffage et de refroidissement alimentés par géothermie en Europe. Nous identifions les principaux défis vers une meilleure intégration de l'énergie géothermique et décrivons les solutions possibles pour une adoption accrue du marché paneuropéen. Les réseaux géothermiques ne peuvent devenir une technologie clé que si des concepts sont disponibles pour traiter à la fois les infrastructures de réseau nouvelles et existantes et le parc immobilier existant.

La energía geotérmica es una opción vital para proporcionar calefacción y refrigeración de fuentes energéticas limpias. La interconexión de la energía geotérmica con el concepto de redes de distribución de calefacción y/o refrigeración ofrece excelentes oportunidades para beneficiarse de economías de escala y multiplicación cuando se trata de descarbonizar el sector de calefacción y refrigeración. Aún así, existen desafíos tanto tecnológicos como socioeconómicos para fomentar la implementación significativa de redes de calefacción y refrigeración suministradas con energía geotérmica en Europa. Hemos identificado desafíos clave hacia una mejor integración de la energía geotérmica, resaltamos y describimos posibles soluciones para una mayor aceptación del mercado Pan-Europeo. Las redes geotérmicas solo pueden convertirse en una tecnología clave si los conceptos están disponibles para abordar las infraestructuras de red nueva y existente y el parque de edificios existente.

1. Introduction

The recent debate on climate change mitigation and geopolitical developments requires new approaches for the decarbonisation of the heating and cooling sector, which is still responsible for almost half of the final energy consumption in Europe and significantly depends on energy imports, above all, fossil fuels [1]. Moreover, the geopolitical developments since February 2022 demand an acceleration of deploying local energy sources to increase the resilience of the energy sector when it comes to supply security and political autonomy. Both, district heating and geothermal energy may provide an important leverage to realize the green energy transition. Nevertheless, geothermal energy supplied heating and cooling networks are covering a minor niche inside the heating and cooling sector of around 2% [2]. Roadmaps towards an increased deployment of geothermal heating and cooling networks (hereinafter referred to as 'geoHC networks') require an understanding of key market drivers covering the technological as well as socio-economic domain. This article outlines the most relevant aspects of pathways towards the increased use of geoHC networks in Europe and discusses the activities performed in the EU COST Action CA18219 'Geothermal-DHC' (***www.geothermal-dhc.eu***), which addresses the integration of geothermal energy in its full technological range in heating and cooling networks.

2. Challenges and opportunities regarding the green transformation of the European heating and cooling sector

Heating and cooling is currently responsible for 49% of the final energy consumption in the European Union [3]. Low temperature space heating represents a heavily underestimated segment, which requires 30% of the final energy consumption as of 2017 [4]. While significant efforts have

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been made in Europe for the decarbonisation of the electricity sector during the past decade, the heating and cooling sector developed more slowly than expected, as the share of renewables currently covers 23% of the final energy demand [5]. A major hurdle concerning the decarbonisation of the heating and cooling sector is related to the lack of transport of heat or cooling over large distances, except for fossil fuels or electricity, which leads to a regulatory responsibility on the regional to national level in most EU Member States.

The central role of heating and cooling in energy transition has also been recognised under the European Green Deal's Climate Target Plan and the 'Fit for 55' package, as without increasing renewable energy shares in this large sector, the EU's energy and climate targets cannot be achieved cost-effectively [6]. A further European initiative is represented by the REPowerEU Plan, a roadmap for mitigating energy market disruption in Europe and reducing the dependence on fossil fuels. The current energy crisis has led governments to put in place short and long-term measures aimed at shielding consumers from the direct impact of the rising energy prices across Europe and to counteract the continuous economic volatility. As highlighted in a recent report by Bruegel [7], a think tank on political and economic issues, in most of the EU countries policies and energy regulations are set at the national level. This means a different approach and general inhomogeneity at European level, not only in regulating energy prices but also towards the outlooks in energy production. The pressure is high for finding solutions to reduce energy imports and fight against climate change impacts.

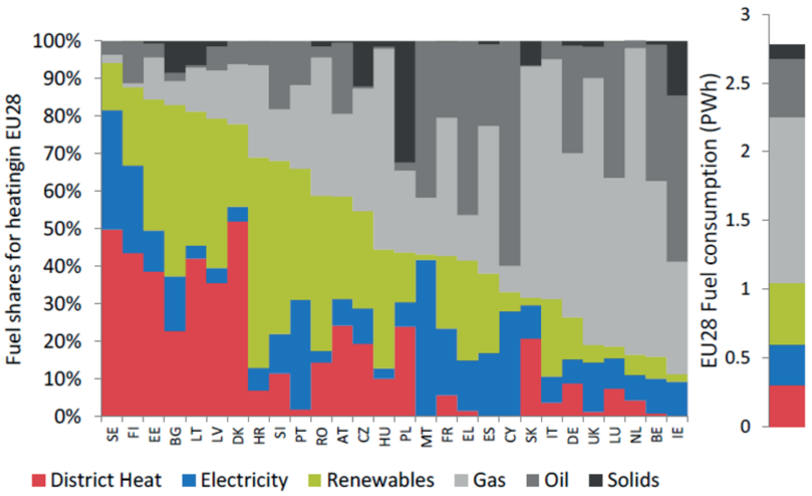

Figure 1: Fuel consumption for space heating in the EU in 2015 [8].

District heating and cooling offer vital options for addressing the both most urgent challenges in the heating and cooling sector: 1) the need to increase low- to no-emissive renewables and 2) the reduction of energy imports. Based on an on overview on the heating sources in Europe, shown in ***Figure 1***, frontrunner countries like Sweden, Finland, Estonia or Denmark have widely reduced the consumption of fossil fuels while implementing district heating and renewable sources, distributed by these. ***Figure 1*** also indicates that countries dominated by individual heat supply systems (Western Europe and Mediterranean Regions) show a strong dependency either on fossil fuels or electricity consumption, which increases energy import dependencies and lowers the resilience of the heating and cooling sector towards disruptive events or crises.

3. Current state and development of district heating and cooling networks

From the different heating and cooling solutions, district heating and cooling (DHC) is one of the main energy related infrastructures for decarbonisation by integrating renewable and carbon neutral energy sources and technologies as well as participating in energy system integration [9].

In principle, a district heating and cooling network is based on a simple concept of pipelines connecting heat sources and sinks to clients. In addition, energy converters, such as heat exchangers or heat pumps and control units at various level of complexity, complement a district heating and cooling network. Since the introduction of the concept in the second half of the nineteenth century, several generations of technological solutions developed. Starting at first-generation (1G) steam-supplied

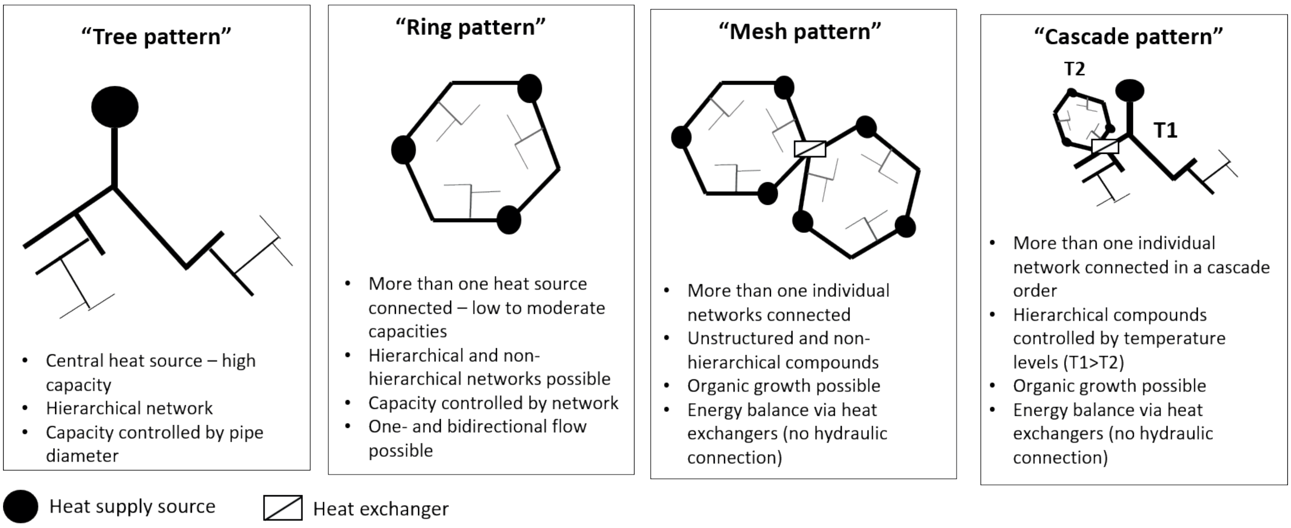
"Tree pattern"
Central heat source – high capacity
Hierarchical network
Capacity controlled by pipe diameter
"Ring pattern"
More than one heat source connected – low to moderate capacities
Hierarchical and non-hierarchical networks possible
Capacity controlled by network
One- and bidirectional flow possible
"Mesh pattern"
More than one individual networks connected
Unstructured and non-hierarchical compounds
Organic growth possible
Energy balance via heat exchangers (no hydraulic connection)
"Cascade pattern"
T2
T1
More than one individual network connected in a cascade order
Hierarchical compounds controlled by temperature levels (T1>T2)
Organic growth possible
Energy balance via heat exchangers (no hydraulic connection)
Heat supply source
Heat exchanger

Figure 2: Evolution of heating and cooling network topographies, offering vital chances for better integration of geothermal energy.

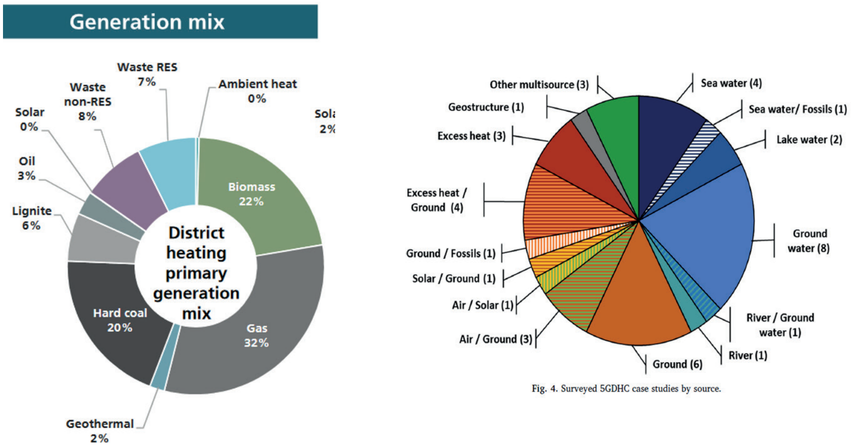

Figure 3: Heat generation mix for all district heating networks in the European Union (left, from [4]) and for 5th generation heating and cooling networks (right, from [11]). The numbers shown in brackets refer to the number of 5th generation networks using a certain heat source (e.g. 'Ground').

district heating networks at temperature levels up to 200 °C, during subsequent decades the energy efficiency (heat loss inside the network) has continuously increased while the network temperatures have been decreased. Reduced temperature levels in turn implied an increase in the diversity of heat sources to supply a district heating network. This also influenced the topography of the network as such. While early-generation networks were organised in hierarchical tree patterns, recent developments have led to ring--based or mesh-based concepts, pursuing de-centralised and unstructured networks (see ***Figure 2***). In contrast to tree-based networks, ring- and mesh-based topographies also increase the flexibility to connect new clients and allow for "organic growth of networks" over certain periods. One needs to consider that tree-based networks cannot be expanded since the capacity of transferring energy is limited by the diameter of its pipelines. However, latest considerations cover the introduction of cascade networks, which connect conventional hierarchical networks with unstructured mesh or ring-based networks via a temperature cascade. In that sense, the conventional heat network is only used for peak load supply or annual balancing.

Modern and efficient district heating and cooling is well placed to benefit from and implement an overall multi-energy system approach, including in connection with city planning. It can also provide flexibility on the electricity market via power-to-heat solutions such as electric boilers or large-scale heat pumps, especially when coupled with thermal storage, or via combined heat and power (CHP) plants, to accommodate renewable electricity production for example. The most concise version of the classification of district heating systems was presented by the study of Lund et al. [10]. The authors distinguished four generations of district heating with rising efficiency and lowering supply temperatures as generations evolve. The proposed concept of the 4th generation DH, among other renewable energy sources and sustainable technologies, considers geothermal energy as a full-fledged energy source to meet heat supply needs. In addition to the four generations defined in [10], there are also many researchers who define modern DHC networks with a supply temperature below 30/40 °C as 5th generation (e.g. [11]).

As of 2018, district heating covered around 13% of the space and domestic water heating supply in the EU27 [4]. As indicated in ***Figure 1***, the share of district heating varies strongly between the different geographic regions inside the European Union. Whilst district heating plays a significant role in Scandinavian and Baltic countries with shares up to 50% of the space and domestic water supply, Western European and Mediterranean countries have no tradition of using this concept. As shown in ***Figure 3***, the heat supply mix inside the district heating segment of the European Union is still dominated by the use of fossil fuels (61% in total), from which natural gas maintains the largest share. The share of geothermal energy inside the heat supply mix in district heating is still negligible in the European Union, at a level of around 2% (***Figure 3***, left). When combining the information given in Figure 1 and ***Figure 3*** it becomes evident that a cluster of regions exists that have an elevated share of existing district heating supplied by fossil fuels. A clean and sustainable transition of the heating and cooling sector may only be realised if solutions for the retrofitting of existing fossil-fuel-supplied district heating systems might be offered. In contrast, low-temperature heating and cooling networks of the 5th generation are important hubs for integrating renewable or clean heat sources (see ***Figure 4***, right). Moreover, the majority of the networks collected

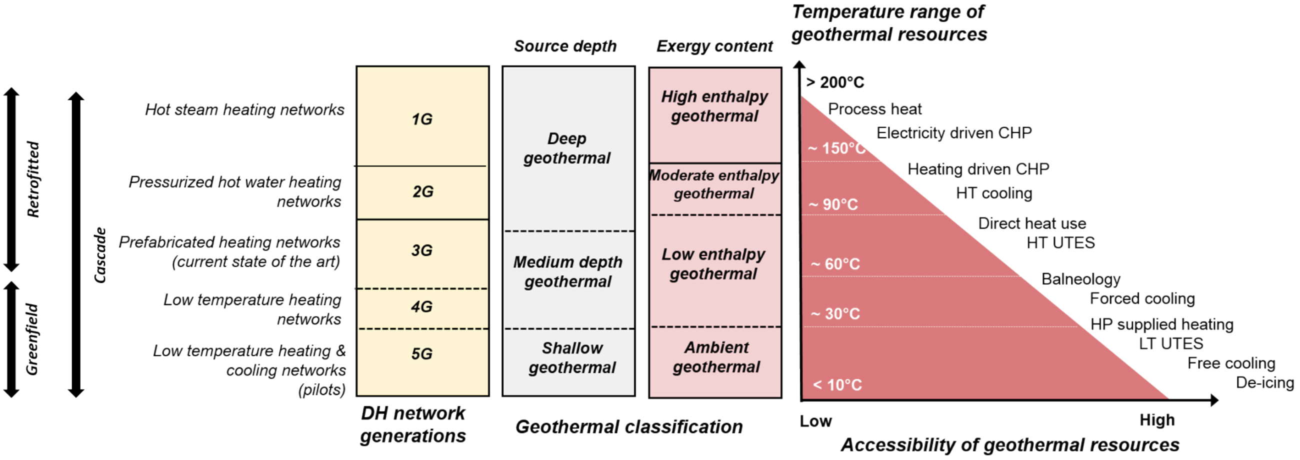

Figure 4: Geothermal energy supplied heating and cooling network classification scheme, based on [13].

and characterised in [11] use subsurface or shallow geothermal concepts as the main or relevant heat source.

4. The use of geothermal energy in heating and cooling networks

Using geothermal energy in district heating networks is not a modern concept. In fact, the first local network supplied by geothermal energy was installed in Chaudes-Aigues (Chaudas Aigas in Occitan) in the Cantal region in south-central France in the 14th century [12].

As shown in ***Figure 4***, geothermal energy may supply the full range of generations referring to district heating (and cooling) networks. However, the supply of 1G (hot steam) and 2G (pressurised hot water) heating networks based on the current technologies at market ready level is limited to only a few hot spot regions in Europe linked to active volcanic activities (e.g., Tuscany or Iceland). As shown by the resource triangle in ***Figure 4***, the accessibility of geothermal resources significantly increases with lowered supply temperature.

From a technical point of view, most options for the inclusion of geothermal energy in heating and cooling networks are given in the temperature range between below 30 °C (5G) and around 90 °C (3G), which also includes the use of underground thermal energy storage (UTES) for seasonal heat storage.

Based on recently published statistics, 364 geothermal-energy-supplied district heating networks [14] as well as at least 40 5th generation heating and cooling networks exist in Europe [11]. The total supply capacity of direct geothermal heat use in heating networks reached 65.6 GW_{th} in 2021 and the number of installed plants grew at a moderate level of +3.6% from 2020 to 2021 [14]. However, according to the statistics collected for the EGEC Market report 2020 [15]), typical use cases for direct heat use in heating networks are still limited to local networks at moderate temperatures (see P50, ***Table 1***). Even cases at the 75th percentile of the data available for 2019 do not exceed installed capacities of 14 MW_{th} and temperatures at the production well of 80 °C.

Table 1: Statistical KPIs of direct geothermal energy used in heating networks in Europe as for 2019 based on the EGEC Geothermal Market report 2020 [14].

KPI	***Sample Size***	***P50***	***P75***
Installed capacity (MW)	*341*	*7*	*14*
Temperature of production well (°C)	*179*	*72*	*80*
Capacity factor (gross heat / installed capacity (kh/yr)	*234*	*2.59*	*3.98*

Based on the available market data, we have calculated a "capacity factor" describing the ratio between the annual heat produced and installed geothermal peak load capacity using the unit 100 hours (kh) per year. Although this represents a synthetic value and not the true operational hours of a geothermal plant per year, this key performance indicator (KPI) indicates the level of integration and optimisation of a geothermal installation inside a heating network. Ideally, geothermal energy provides base load supply at stable capacity levels to reduce the levelised cost of heating (LcoH). This is reflected by capacity factors above 5 kh/yr. Low capacity factors either indicate a significant gap between peak load capacities and annual heat production (e.g., by operating in monovalent heat supply mode, which is affected by high investment costs) or reduced annual operational hours, increasing the LCoH.

5. Business interest in geoHC networks

As suggested by many recently published scientific articles, social media networking platforms can deliver valuable and high-quality data regarding various scientific and business sectors [16]. In this work, the authors studied companies or organisations registered on LinkedIn which based on their LinkedIn profiles contain selected keywords to identify existing trends in the geothermal sector in EU-27 countries. More specifically, the four keywords searched for were "geothermal", "district heating", "drilling services" and "energy supplier"; a keyword could be found in any section of a company's profile (e.g., title, description or specialties offered by the respective company).

In total, 470 companies related to "district heating", 510 to "drilling services" and 699 to "geothermal" were found and extracted from the LinkedIn data search, which took place in July 2022. At this point, it should be noted that some of the identified companies are assigned to more than one of the selected keywords. Renewables & Environment was the leading industry sector in every dataset except for "drilling services", where the vast majority of companies are in the Oil & Energy sector. All keywords selected show a continuous growth of business foundations or re-organisation in the past decades. While

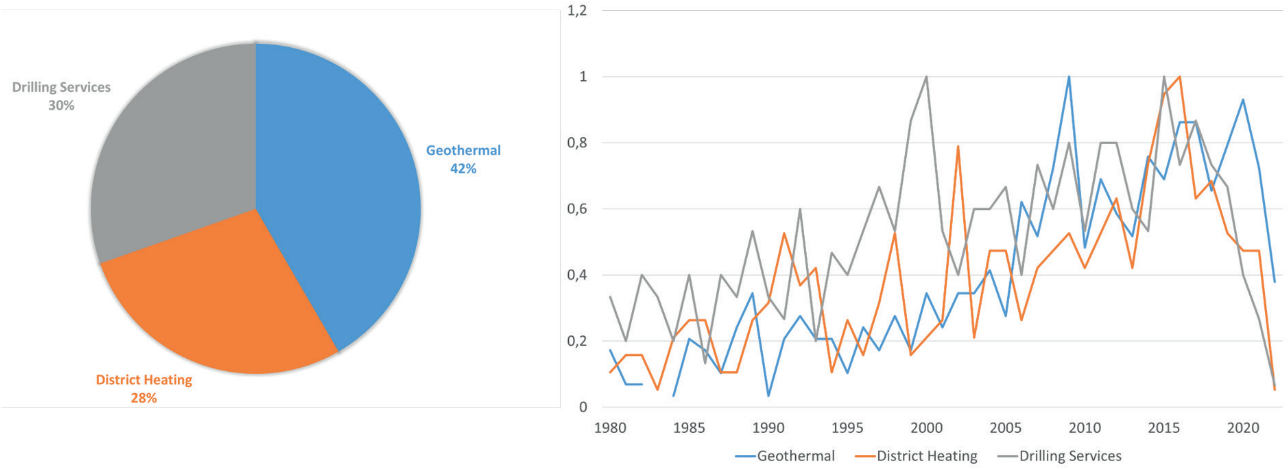

Figure 5: Business trends based on LinkedIn profile trends for the keywords "Drilling Services", "District Heating" and "Geothermal". Relative share of company profiles linked to 3 keywords (left) and a time line of company foundation or re-organisations since 1980 showing the normalized relative frequency for each key word (right).

companies related to drilling services reached a peak at the beginning of this millennium, triggered by increasing oil & gas prices, businesses offering geothermal services peaked ahead of the financial crisis starting in 2008. We want to point out that this peak is presumably linked to the planning and installation of individual ground-source heat-pump installations rather than to services related to the use of geothermal energy in heating and cooling networks. Nevertheless, after the financial shock of the late 2000s the business sector related to geothermal energy started to grow continuously in the past years almost reaching the all-time peak of 2008. This also applies to businesses related to "district heating". We observe a significantly increasing business interest in the past decade, with a peak in new companies just a few years ago in 2017. Referring to business sizes, geothermal services are dominated by small enterprises with up to 10 employees, according to the investigated LinkedIn profiles. This mostly reflects planners and exploration service providers as well as installers related to ground-source heat pumps. District heating service as well as drilling service providers indicate small to medium-sized enterprises showing peaks in the category of 11 to 50 employees.

Table 1: Statistical KPIs of direct geothermal energy used in heating networks in Europe as for 2019 based on the EGEC Geothermal Market report 2020 [14].

Market barrier	**Domain**	**Sub-domain**
Geothermal concepts at high market readiness level strongly depend on specific geological conditions (e.g., high enthalpy resources or aquifer systems)	*Technology*	*Access to resources*
High CAPEX and associated financial and operation risks during the development and use of geothermal sources		
Lack of demonstration and pilot sites to increase the market readiness level of promising technologies for a better inclusion of geothermal energy, such as UTES		
Upscaling of well-developed individual concepts to increase the capacity of geoHC networks and facilitate the integration of geoHC networks in urban areas		*System integration*
Lack of replicable concepts to optimise the use of geothermal energy in geoHC networks to reduce LCoH		
Limited access to information on geothermal resources and options	*Societal*	*Policy & Governance*
Unfit or fragmented legal framework, increasing the development efforts and time periods of geothermal developments		
Development periods exceeding policy circles, which lead to stop-and-go policies		
Misleading and prejudged opinions of market actors and stakeholders, leading to low levels of awareness of and trust in geoHC networks		*Awareness & Acceptance*
Higher complexity associated with increased investment risks compared to other renewable energy sources bearing the risk of "wasting high enthalpy carriers for low enthalpy uses"		*Financing & Business*

6. Main barriers towards implementation of geothermal energy in heating and cooling networks

Both geothermal energy and district heating only play a minor role so far in the European heating and cooling sector. Moreover, the combination of geothermal and district heating and cooling ('geoHC networks') represents a niche with a share of 2% of the end energy supply [4]. In interactions with decision makers and investors relevant to the heating and cooling sector, the main arguments can be summarised as "too expensive", "too complicated" or "unsuitable capacities and temperature levels".

Therefore, we created a list of significant market barriers hindering investment in geoHC networks in ***Table 2***, based on data from workshops organised by the EU COST Action CA18219 Geothermal-DHC. We aligned the identified barriers to two main domains: the technological and the societal domain; the impact of the latter is even more relevant as it triggers or hinders technological development.

Apart from efforts made concerning the integration of geothermal energy in low temperature heating and cooling networks, developments to increase the technological scope of geothermal or reduce investment costs and risks progressed more slowly mostly due to lack of attention by decision makers to the clean transformation of the heating and cooling sector. In the past decade, more attention has been paid to the integration of renewables into the electricity sector in Europe. The long development periods of geothermal projects in general resulted in 'stop-and-go' policies when it comes to financial incentives or other public support. The term 'stop-and-go policies' covers ambiguous measures through change of government and especially applies when development periods of geothermal projects exceed legislation periods. Many European countries also face unfit regulations and fragmented regulatory frameworks that neglect geothermal heat as a relevant source of energy. The recent multiple crises have led to increased interest in using geothermal energy in heating and cooling networks to substitute fossil fuels, especially gas boilers. However, due to shortcomings in the market development efforts in the past years, services needed for the rollout of geoHC networks in Europe are limited and require significant ramp-up periods.

7. Pathways for more geothermal heating and cooling networks in the future

During the past decades, the so-called "low hanging fruits" for the use of geothermal energy in heating and cooling networks have been harvested. We conclude that balneology has been an important driver in many European countries to stimulate investment in geoHC networks. The same applies to the capitalisation of "unsuccessful" hydrocarbon wells, which showed instead the occurrence of natural thermal water used for recreation and energy supply purposes. This is also indicated in the statistic characteristics related to direct geothermal use in heating and cooling networks, as shown in ***Table 2***. In addition, the production of electricity has been another important market driver, especially in high enthalpy zones of Europe like Iceland or Turkey, leading to the implementation of combined heat and power (CHP) applications. Important development steps have been made in the past years to introduce the concept of 5th generation heating and cooling networks.

Fostering the use of geothermal energy in heating and cooling networks across Europe requires shifts of paradigm to expand and refine the concept of geother-

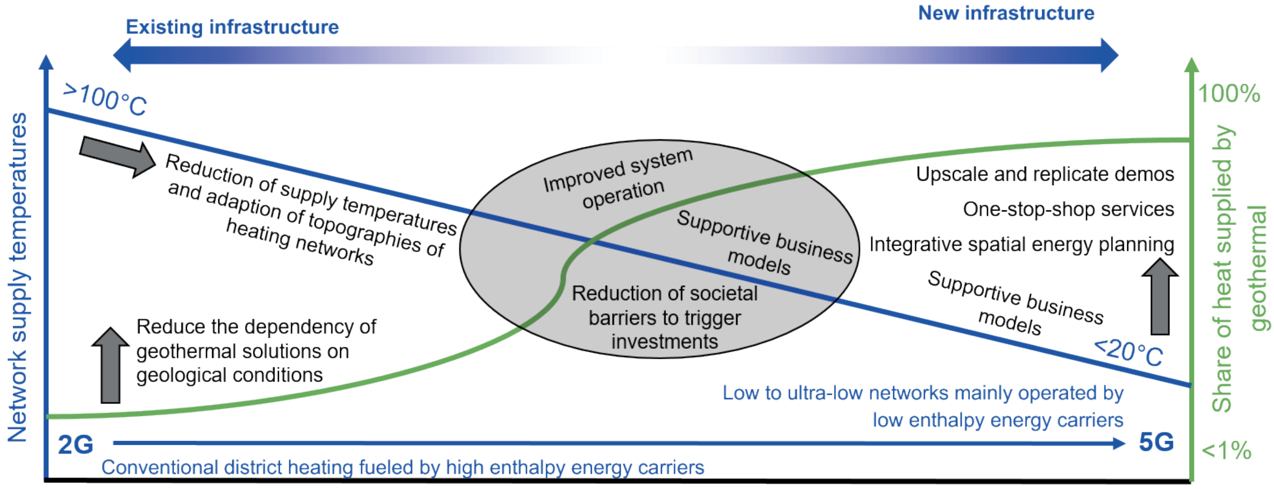
Existing infrastructure
New infrastructure
Network supply temperatures
>100°C
Reduction of supply temperatures and adaption of topographies of heating networks
Reduce the dependency of geothermal solutions on geological conditions
Improved system operation
Supportive business models
Reduction of societal barriers to trigger investments
Upscale and replicate demos
One-stop-shop services
Integrative spatial energy planning
Supportive business models
<20°C
Low to ultra-low networks mainly operated by low enthalpy energy carriers
2G
5G
Conventional district heating fueled by high enthalpy energy carriers
100%
<1%
Share of heat supplied by geothermal

Figure 6: Generalised scheme of pathways towards better integration of geothermal energy in heating and cooling networks.

mal energy use in heating and cooling networks. We propose that future geoHC networks ideally show the following characteristics:

i. Geothermal is part of multivalent heating and cooling networks harvesting and capitalising on-site available heat sources. Geothermal energy may play a twofold role by providing base load and large volume, seasonal heat storage (UTES);
ii. New network topographies allow for organic growth and cascade-based interlinking of district heating networks with unstructured local networks to support the decarbonisation of existing district heating networks and increase the energy balance of individual networks;
iii. Heat pumps at different temperatures, capacity levels and positions within the geoHC network (central as well as de-central placement) will act as modulators to support energy conversion inside the network and between the network and clients. This will lead to the increased flexibility and adaptability of heating and cooling networks.

Efforts to increase the share of geothermal energy in heating and cooling networks may not just cover new infrastructure but also need to address existing heating networks or buildings previously supplied by individual boilers. Due to the nature of geothermal energy, there are system limits for supplying heating networks, which are given by the temperature and capacity level. As indicated in Figure 6, the integration of geothermal energy in existing infrastructure will heavily depend on measures to reduce the required supply temperatures. Two current technological developments make the future integration of geothermal energy in district heating even more attractive: the trend towards lower supply temperatures in district heating networks [10] and the increasing commercial availability of high-temperature heat pumps [17]. Both trends enable the significantly higher thermal capacity of a geothermal project, since the thermal water can be further cooled down and more heat can be provided towards a district heating network. We identify critical tipping points at supply temperatures levels between 90 °C and 100 °C. On the other hand, technological research and development focusing on engineered geothermal solutions (e.g., enhanced geothermal systems, deep closed loop systems) may reduce the dependency on natural hot water and steam and provide vital options to make geothermal supply accessible to retrofitted existing heating networks, even at enhanced supply temperature levels. In addition, cascade-related network topographies (see also ***Figure 2***) help increase the overall supply capacity of a district heating network and may compensate for the capacity losses of tree-based networks due to the reduction of the grid temperature at the same pipeline diameters. As mentioned earlier in this article, cascade use of local, low-temperature heating and cooling networks (4G to 5G) connected to a conventional district heating network (2G to 3G) enable the harvesting of local heat sources – including geothermal – and the application of seasonal heat storage for balancing reasons, including underground thermal energy storage.

Heating networks operating at temperatures below 100 °C have access to a wider range of geothermal technologies, including conventional hydrogeothermal use. We estimate the level of exploitation of known thermal aquifers in Europe at around 10%, which is in line with the conclusions of the GeoDH project (***http://geodh.eu***) that around 20% of the European population can be supplied by hydrogeothermal district heating. This segment of geoHC networks is predominately affected by insufficient policies and governance structures to trigger future investment. Accounting for the long development periods of geothermal projects (3 to 7 years), measures to improve the socio-economic boundary conditions need to be put in place immediately to achieve impacts before 2030. The European Commission could set important cornerstones by developing a European strategy on geothermal energy, for instance. On the other hand, development periods of geoHC networks can be reduced not only by supportive policies but also by sustainable business concepts. In that context, geothermal developers may apply strategies from the hydrocarbon industry to develop portfolios of geothermal heating plants in a certain region instead of always creating individual, isolated projects. This would also offer instruments to reduce the economic risk associated with the development of geothermal heating plants. Communities and conventional energy suppliers who are not experts in geothermal would in turn shift from investors to clients of geothermal heat supply in heating networks.

Low- to ultra-low-temperature heating and cooling networks (4G to 5G) in turn are vital options for greenfield solutions and new networks connecting existing buildings not yet supplied by district heating. According to [11], at least 40 fifth generation heating and cooling networks exist in Europe and the number is rapidly growing. The individual components of such networks (e.g., borehole heat exchangers, operational control components) are well developed on the level of an individual network. Further developments are needed to make the network topography more adaptive for connecting individual networks to meshes or cascade networks. Moreover, the successful roll-out of such networks in Europe also depends on the development of business models and one-stop-shop service providers, especially addressing urban areas in Europe for offering alternative solutions to individual fossil-fuel boilers in houses and apartments. This of course requires increased efforts to accelerate the retrofitting of buildings as well as more strategic spatial energy planning in urban areas. Eventually, new business solutions to foster 4G and 5G networks supplied by geothermal energy need to be aligned with spatial energy plans, since geothermal installations such as borehole heat exchangers will very likely require the use of public space (e.g., parks, pathways or streets) in densely settled areas.

Acknowledgement

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CROWDTHERMAL services for the energy transition and the Green Deal

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The European Green Deal, the EU's climate and economic policy that aims at transforming Europe into the first climate-neutral continent by 2050, focuses on clean energy and climate action. However, the energy transition will not happen without citizens. The CROWDTHERMAL project places citizens at the centre of energy supply development. The project has elaborated web tools for community investors, local authorities and project developers. Through the "Core Services" portal, they can identify the most efficient social engagement strategies and financial instruments; carry out a self-assessment on financial and risk mitigation; discover the parameters for economic modelling of projects; learn the fundamental aspects for the successful implementation of a geothermal project; and browse a meta-database of geothermal projects with the option to self-register.

Le Green Deal européen, la politique climatique et économique de l'UE qui vise à faire de l'Europe le premier continent climatiquement neutre d'ici 2050, se concentre sur l'énergie propre et l'action climatique. Cependant, la transition énergétique ne se fera pas sans les citoyens. Le projet CROWDTHERMAL place les citoyens au centre du développement de l'approvisionnement énergétique. Le projet a élaboré des outils web pour les investisseurs communautaires, les autorités locales et les développeurs de projets. Grâce au portail « Core Services », ils peuvent identifier les stratégies d'engagement social et les instruments financiers les plus efficaces ; procéder à une auto-évaluation des finances et de l'atténuation des risques ; découvrir les paramètres de modélisation économique des projets ; apprendre les aspects fondamentaux pour la mise en œuvre réussie d'un projet géothermique; et parcourir une méta-base de données de projets géothermiques avec la possibilité de s'inscrire soi-même.

El Pacto Verde Europeo, la política climática y económica de la UE que tiene como objetivo transformar a Europa en el primer continente climáticamente neutral para 2050, se centra en la energía limpia y la acción climática. Sin embargo, la transición energética no ocurrirá sin ciudadanos. El proyecto CROWDTHERMAL sitúa a los ciudadanos en el centro del desarrollo del suministro energético. El proyecto ha elaborado herramientas web para inversores comunitarios, autoridades locales y desarrolladores de proyectos. A través del portal "Core Services" (Servicios centrales), pueden identificar las estrategias de participación social e instrumentos financieros más eficientes; A fin de realizar una autoevaluación financiera y de mitigación de riesgos; descubrir los parámetros para la modelización económica de proyectos; aprender los aspectos fundamentales para la implementación exitosa de un proyecto geotérmico; y explore una meta-base de datos de proyectos geotérmicos con la opción de auto-registro.

1. Introduction

1.1 Political context

Research and deployment of renewable energies have never been more urgent. Globally, humanity is faced with a threatening climate change and energy prices have never been so high, while a growing number of countries are becoming painfully aware of geopolitical energy dependencies.

Policy and industry are slowly reacting, moving into an energy transition. The predominant regime of fossil fuel is gradually being downsized. Investment is directed to the new energy system based on renewable energy sources, infrastructure, new business models and opportunities. This is a historical and systemic shift where all sources of energy have to find their place. Geothermal energy is definitely one of these, with a large growth potential for heating, cooling and power generation.

EU policy is on the forefront driving this systemic shift, addressing both supply and demand of energy. In December 2019, the European Commission launched the European Green Deal [1], a comprehensive policy to accelerate the energy transition in the EU ensuring a climate-neutral EU by 2050. Investment, regulations and reforms are mobilised in parallel to create the right framework conditions for both industry and consumers. More recently, responding to the geostrategic energy dependency on Russia, the EU launched the RePowerEU policy, which includes an ambition to double the deployment of geothermal in the EU [2].

However, despite these high-level political initiatives, ***Figure 1***, the deployment of renewable energy faces several blockages on the ground. Adequate finance is not always available or flexible enough. And even more fundamentally, citizens are not always keen on the construction of new sites of renewable energy generation. While globally accepting the need for clean and diversified energy, citizens are protesting against new production sites close to their neighbourhoods. In several EU member states, new investment projects in wind, solar or geothermal energy have been vetoed by local municipalities. This dynamic tends to exacerbate the tension between urban and rural areas, where the latter are net suppliers of energy.

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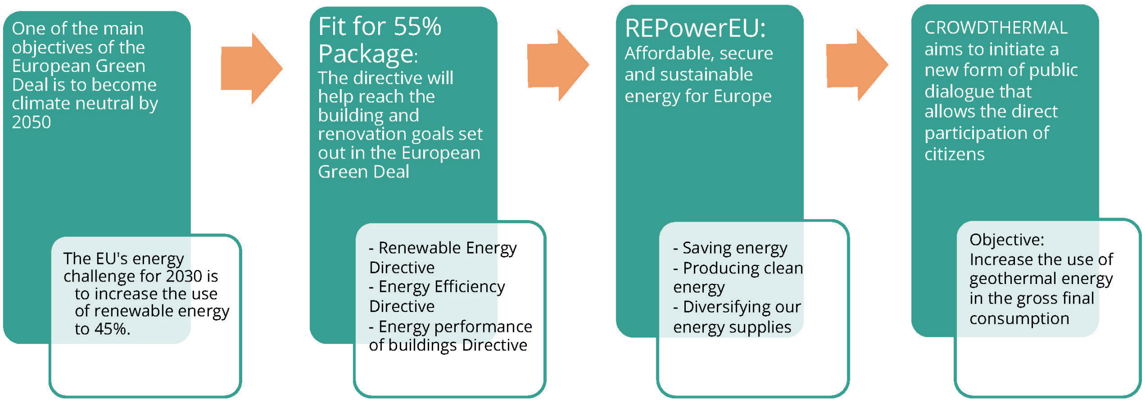

One of the main objectives of the European Green Deal is to become climate neutral by 2050
The EU's energy challenge for 2030 is to increase the use of renewable energy to 45%.
Fit for 55% Package:
The directive will help reach the building and renovation goals set out in the European Green Deal
- Renewable Energy Directive
- Energy Efficiency Directive
- Energy performance of buildings Directive
REPowerEU:
Affordable, secure and sustainable energy for Europe
- Saving energy
- Producing clean energy
- Diversifying our energy supplies
CROWDTHERMAL aims to initiate a new form of public dialogue that allows the direct participation of citizens
Objective:
Increase the use of geothermal energy in the gross final consumption

Figure 1: CROWDTHERMAL project in the European policy context.

1.2. Geothermal energy in Europe

Geothermal energy is a resource that has potential for development in many countries around the world. However, despite its versatility and economic viability, this resource faces numerous obstacles that hinder its deployment and its capacity for achieving a similar degree of use as its other renewable and clean energy counterparts.

In Europe, the status of geothermal utilisation and potential ranges from direct use of hydrothermal resources in sedimentary basins to high-temperature geothermal resources found in volcanic areas. Sedimentary basins are present in multiple European countries, while there is a lower number of European countries characterised by young volcanic activity.

Shallow and low-temperature geothermal is available almost everywhere in Europe and is commonly harnessed through GSHP (Ground Source Heat Pump) installations [3]. There are several types of geothermal energy technologies and different classification schemes. ***Figure 2*** summarises the classifications adopted by the CROWDTHERMAL consortium [4].

The uses of geothermal energy are determined by the temperature of the resource and the exploitation technology. ***Figure 2*** indicates some uses of geothermal energy. Based on the EGEC 2019 European Country Reports, the share of installed capacity of shallow geothermal systems (mostly GSHP) amounts to 66.5%, direct use 26.2% and electricity 7.3% [5]. Despite its huge potential to supply sustainable, decentralised and low-carbon baseload energy for electricity, heating and cooling, geothermal still plays a marginal role in the European energy mix.

According to the EGEC country fiches [6] for the EU Member States we can find potential for geothermal resources in most EU countries:

Austria's geothermal resources are particularly well suited to the deployment of deep geothermal projects for heating and cooling, and allow for greater use of geothermal electricity in the long term. The geothermal resources of Austria are particularly well distributed throughout the territory.

Belgium's identified geothermal resources are mostly located in the northeast and the south of the country. They are well suited for deep geothermal heating and cooling projects.

The Czech Republic's available geological data reveal the availability of resources dotting the country from the northwest to the southeast.

Croatia's geothermal resources are well identified and primarily located in the north, within the Pannonian Basin (which is the source of many Central and Eastern European countries' geothermal resources). These resources are suitable for heating and cooling and for electricity production.

Denmark's deep geothermal resources, notably suitable for heating and cooling, are well identified and well distributed throughout the country.

Finland is particularly well suited for shallow geothermal developments, as its geology allows for more cost-effective drilling, and its climate justifies more easily the larger investments required by this heating and cooling technology. For deep geothermal, Finland does not have significant resources that have been identified so far. However, some ongoing projects for deep geothermal heating and cooling illustrate that there are deep geothermal resources available in the country, notably near the capital region of Helsinki.

France has geothermal resources well

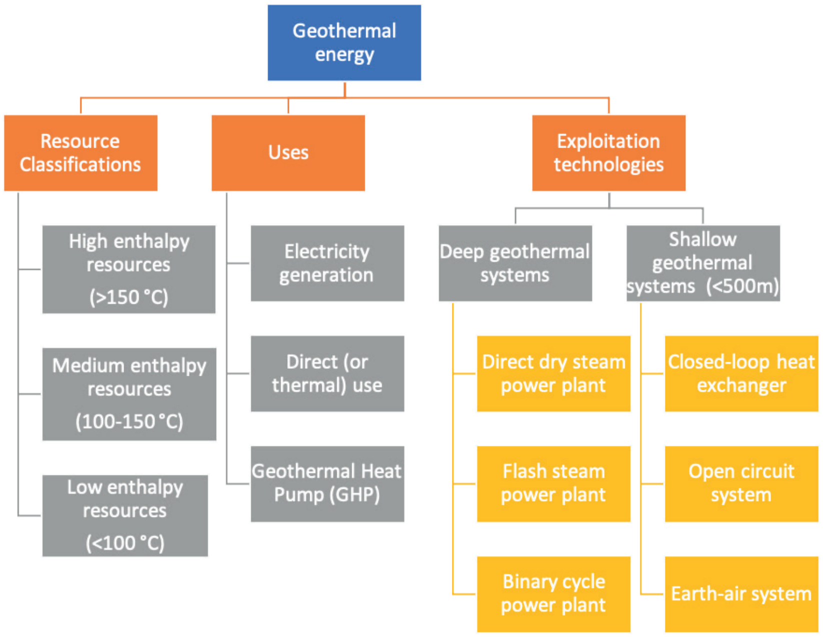

Geothermal energy
Resource Classifications
Uses
Exploitation technologies
High enthalpy resources (>150 °C)
Medium enthalpy resources (100-150 °C)
Low enthalpy resources (<100 °C)
Electricity generation
Direct (or thermal) use
Geothermal Heat Pump (GHP)
Deep geothermal systems
Shallow geothermal systems (<500m)
Direct dry steam power plant
Flash steam power plant
Binary cycle power plant
Closed-loop heat exchanger
Open circuit system
Earth-air system

Figure 2: Classification of geothermal energy projects.

distributed across the territory. A particularly important contribution can be provided in the Paris area for heating and cooling and in Alsace or overseas territories for electricity. Shallow systems can be installed all across the country for heating and cooling.

Germany's identified deep geothermal resources are distributed in the north and the south of the country. Currently, the Rhineland and Bavaria are the areas where most of the deep geothermal capacity has been developed.

Greece's deep geothermal resources identification still requires extensive exploration work on Greece. In terms of resources, the northeast of the country is characterized by good potential for geothermal electricity. In addition, a major geothermal resource is shallow geothermal systems, which can provide renewable cooling.

Hungary's geothermal resources are well known, are well distributed throughout the territory, and are of high quality. This makes Hungary a country extraordinarily well suited to massive reliance on geothermal energy, a dispatchable, flexible source of renewable heating and cooling and electricity.

Deep geothermal resources have been identified in Ireland, notably around the Dublin region, where geothermal district heating developments could take place.

Italy's resources have been exploited for a century to produce geothermal electricity. Currently, Italy's geothermal industry is concentrated in the high-temperature resource of the Tuscany region. Italy also has additional potential for electricity production in other areas of the country. The largely undeveloped potential for Italy is geothermal for heating and cooling.

The Netherlands' geothermal resources are distributed throughout the territory, although unevenly so. They are however located suitably for a large proportion of the Dutch population to be potentially able to cover its heating and cooling needs through geothermal energy. In addition, the Netherlands has a potential to develop geothermal electricity production at competitive costs in the medium term.

Poland's geothermal resources are well identified, notably in the Polish Lowland at the centre of the country and in the south (inner Carpathian area). Other prospective resources are being explored in the Sudetes regions, outer Carpathian and Carpathian for deep geothermal. Altogether, Poland's potential in the short to medium term is primarily aimed at heating and cooling applications, although resources allow for localised geothermal electricity developments.

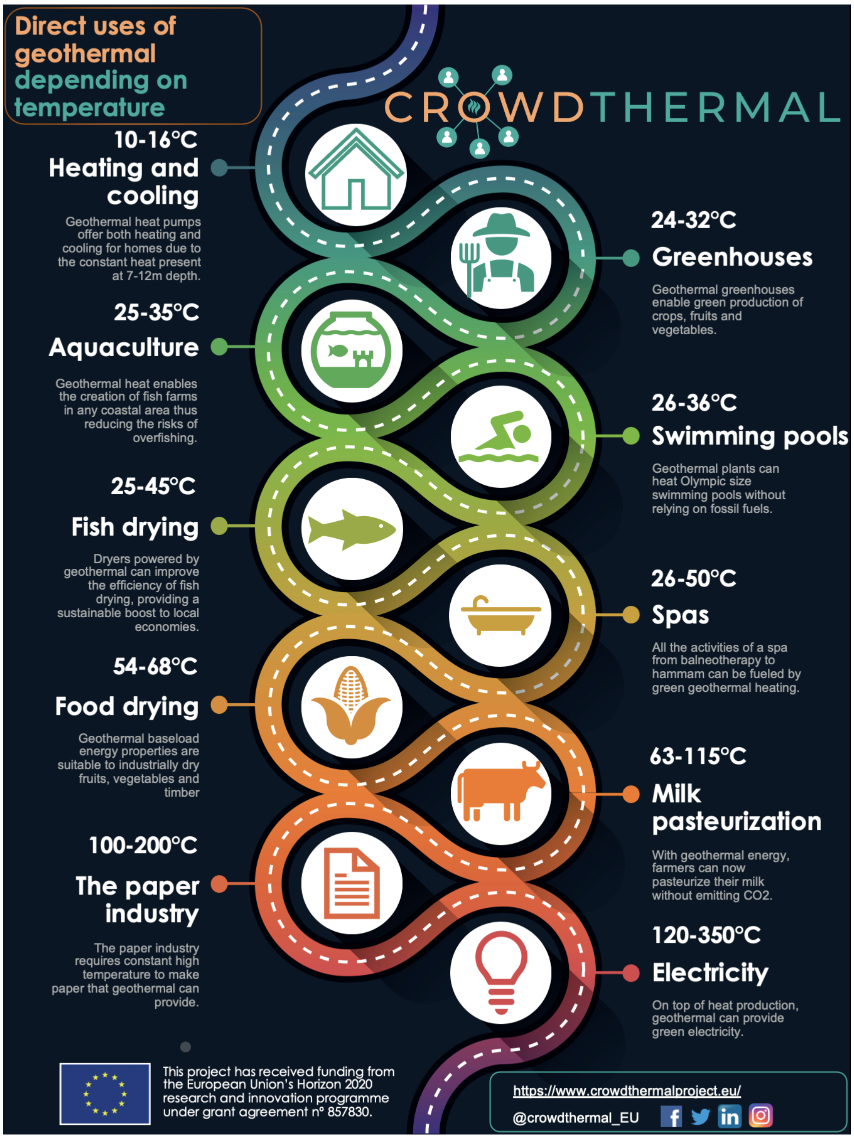
Portugal has high-quality resources available for geothermal electricity in the Azores, where more developments can be undertaken. The country also has some identified resources in parts of the country, notably in the Lisbon area, where deep geo-thermal resources would be available for heating and cooling uses. Shallow geothermal can be developed across the whole country, and is notably a proven solution to provide renewable cooling.

Romania's deep geothermal resources for heating and cooling have been identified and developed in the northwest of the country. Romania also has the potential to develop some geothermal electricity capacity, and shallow geothermal technologies can be developed throughout the country.

Slovenia has significant geothermal energy resources, in particular for deep geothermal projects for heating and cooling. Geothermal electricity projects are possible. Finally, shallow geothermal projects can be implemented across the country, which also has climatic conditions and geology particularly suited to this technology.

Slovakia has significant geothermal energy resources that are identified, in particular for deep geothermal projects for heating and cooling. Moreover, the known geological resources in Slovakia allow for the development of some geothermal electricity projects in the short to medium term. Finally, shallow geothermal projects can be implemented across the country.

Mainland Spain has some prospects for EGS, while the Canary Islands are likely home to the largest resource for rapid deployment, with well-documented high-



Geothermal heat pumps offer both heating and cooling for homes due to the constant heat present at 7-12m depth.

Geothermal greenhouses enable green production of crops, fruits and vegetables.

Geothermal heat enables the creation of fish farms in any coastal area thus reducing the risks of overfishing.

Geothermal plants can heat Olympic size swimming pools without relying on fossil fuels.

Dryers powered by geothermal can improve the efficiency of fish drying, providing a sustainable boost to local economies.

All the activities of a spa from balneotherapy to hammam can be fueled by green geothermal heating.

Geothermal baseload energy properties are suitable to industrially dry fruits, vegetables and timber

With geothermal energy, farmers can now pasteurize their milk without emitting CO2.

The paper industry requires constant high temperature to make paper that geothermal can provide.

On top of heat production, geothermal can provide green electricity.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement n° 857830.

https://www.crowdthermalproject.eu/
@crowdthermal_EU

Figure 3: Geothermal uses depending on resource temperature.

temperature resources. For deep geothermal heating and cooling some resources have been identified in mainland Spain, notably in the north.

Sweden is particularly well suited for shallow geothermal developments, as its geology allows for more cost-effective drilling, and its climate justifies more easily the larger investments required by this heating and cooling technology. Shallow geothermal systems can be deployed throughout the whole country. For deep geothermal, Sweden has identified resources in the south.

Across Europe, gothermal energy is being used in different industries with great success. ***Figure 3*** is an infographic from CROWDTHERMAL which illustrates some examples of the use of geothermal energy depending on the temperature of the resource.

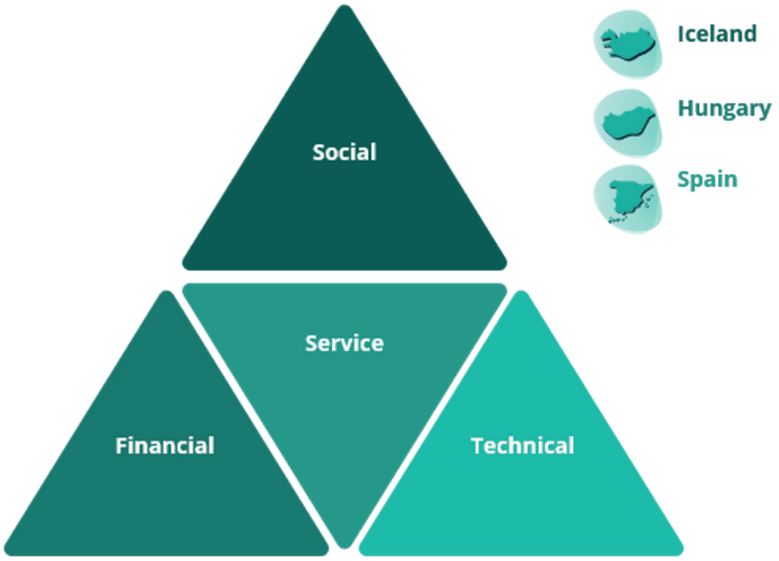


Figure 4: Schematic development of Core Services based on the three angles: social, financial, and technical.

1.3. CROWDTHERMAL project

To promote further geothermal market development in Europe, the EU-funded CROWDTHERMAL project ('Community-based development schemes for geothermal energy') aims to empower the public to participate in the development of geothermal projects through social engagement tools and alternative financing schemes like crowdfunding.

CROWDTHERMAL is a project funded under the European Union's Research and Innovation programme Horizon 2020 – Grant Agreement no. 857830. It is a 40-month project led by the European Federation of Geologists (EFG), with a consortium of 10 partners from 7 different European countries. The project started on 1 September 2019 and will end 31 December 2022. The topic for the call of the project was market uptake support, focusing on the area of building a low carbon, climate resilient future (LC).

The CROWDTHERMAL project is based on multidisciplinary research, combining engineering and technical knowledge on geothermal energy with social science, psychology, innovative finance engineering and social innovation. This is possible thanks to a multidisciplinary consortium team, where relevant institutions from several European countries joined up:

- European Federation of Geologists, EFG: Project coordinator, European professional NGO
- Institute for Future Energy Systems gGmbH, IZES: Germany, research institute
- University of Glasgow, UoG: UK, research institute
- Vulcan Energy Subsurface Solutions GmbH, VES: Germany, SMEs
- La Palma Research Centre for Future Studies, SL, LPRC: Spain, SMEs
- CrowdFungindHub BV, CFH: Netherlands, SMEs
- District Heating Company of Szeged, SZDH: Hungary, energy company
- Spanish Geothermal Technology Platform, GEOPLAT: Spain, NGO
- Geothermal Research Cluster, GEORG: Iceland, research centre
- EIMUR: Iceland, NGO

This team includes geology associations, research centres on social and technical aspects of geothermal energy, geothermal industry, and SMEs specialised in financial engineering. The geographical spread is further enhanced by "linked third parties", i.e., collaborating geological associations from 17 European countries. Finally, the project benefitted from an Advisory Board with 10 members representing the societal, technical and financial sectors.

There is a clear need to learn more about public engagement and the social acceptance of renewable energy, focusing here on geothermal energy in its different forms. Equally, there is a positive correlation between public engagement and new forms of financing of renewable energy projects. With the right framework conditions, citizens not only accept renewable energy but actively promote it, engaging as co-investors. Community funding and innovative use of crowdfunding both require and increase public engagement and trust.

One key outcome of the project is to develop core services for social-media based promotion and alternative financing of geothermal projects, working closely with existing structures and conventional players. The Core Services outcome is based on the three pillars of work: social, financial, and technical (***Figure 4***).

- Social: new forms of public dialogue to tackle concerns and increase interest in geothermal energy;
- Financial: empowering citizens to directly participate in the development of geothermal projects with the help of alternative financing, such as crowdfunding;
- Technical: techniques to gain public trust, risk mitigation and transparency of geothermal projects.

The CROWDTHERMAL project validates its findings with the help of three case studies in Iceland, Hungary and Spain. These case studies of CROWDTHERMAL have the following characteristics:

- Spanish case studies: By using geothermal heat pumps as well as ventilation equipment with heat recovery, the project Edificio Arroyo Bodonal in Tres Cantos, Madrid provides heating, cooling and domestic hot water to 80 houses. The project EAI 310 building, sited in the middle of Madrid's Chamartín district, consists of 220 apartments distributed in several buildings that are being provided with energy from a shallow geothermal system.

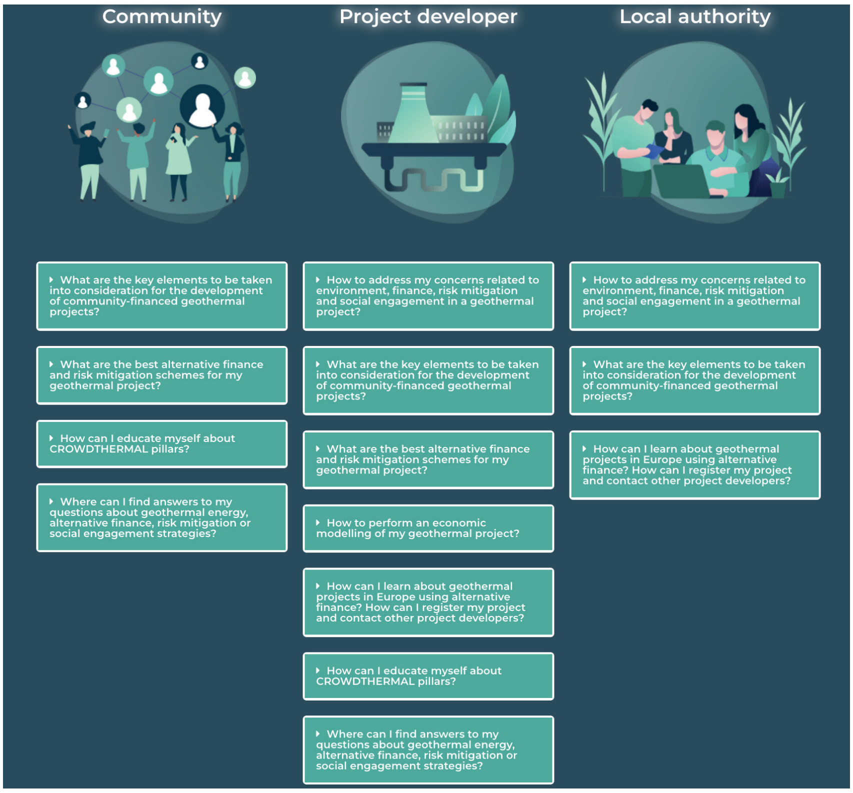
- Hungarian case study: The geothermal energy project from Hungary consists of nine projects that each target multiple, currently gas-based heating circuits in the district heating system of the city of Szeged. A total of 27 geothermal (9 production and 18 injection) wells are being constructed, whereby the supply of 26,338 end users (of the 27,257 total) will be based on renewable energy.
- Icelandic case study: The aim of the project Community Greenhouse is the illustration of how crowdfunding can increase the share of geothermal energy in food production and processing and therefore increase the region's sustainability with value creation.

The Core Services have been delivered to facilitate access to new financial instruments. The target groups are:

- Communities of citizens keen to become actors in the energy transition process. The benefits for these communities could be economical or environmental;
- Geothermal project developers interested in involving the community to increase commitment and/or fundraising;
- Local authorities interested in involving the community to develop a Sustainable Energy (and Climate) Action Plan 2030.

2. Core Services

The interdisciplinary combination of expertise in the project has resulted in the development of a set of key outcomes of the project that were converted into web tools - the CROWDTHERMAL Core Services. Their purpose is to help the target audiences in the development of new geothermal projects in Europe and they are available on the project website under the Core Services Portal. In this portal, users can explore and access all Core Services, though there is a suggested division of the tools per target audience according to the potential benefits and relevance for the stakeholder group. These target audiences were defined by project partners as geothermal project developers, communities of citizens who are interested in geothermal energy, and local authorities, as indicated in *Figure 5*.



Community

- What are the key elements to be taken into consideration for the development of community-financed geothermal projects?
- What are the best alternative finance and risk mitigation schemes for my geothermal project?
- How can I educate myself about CROWDTHERMAL pillars?
- Where can I find answers to my questions about geothermal energy, alternative finance, risk mitigation or social engagement strategies?

Project developer

- How to address my concerns related to environment, finance, risk mitigation and social engagement in a geothermal project?
- What are the key elements to be taken into consideration for the development of community-financed geothermal projects?
- What are the best alternative finance and risk mitigation schemes for my geothermal project?
- How to perform an economic modelling of my geothermal project?
- How can I learn about geothermal projects in Europe using alternative finance? How can I register my project and contact other project developers?
- How can I educate myself about CROWDTHERMAL pillars?
- Where can I find answers to my questions about geothermal energy, alternative finance, risk mitigation or social engagement strategies?

Local authority

- How to address my concerns related to environment, finance, risk mitigation and social engagement in a geothermal project?
- What are the key elements to be taken into consideration for the development of community-financed geothermal projects?
- How can I learn about geothermal projects in Europe using alternative finance? How can I register my project and contact other project developers?

Figure 5: CROWDTHERMAL Core Services by target groups.

The available Core Services are the following:

- Decision support tool: The tool addresses the concerns related to the environment, finance, risk mitigation and social engagement in a geothermal project. It is a toolbox for geothermal project developers and public authorities to support decisions at different stages of the project. This tool is a workflow with a set of guiding questions with regards to project phase, objectives, social engagement, alternative finance, risk mitigation and environmental aspects. The workflow is tailored according to the answers provided by the user based on their situation, which will lead them to tailored recommendations at the end of the process. Link for tutorial: ***https://youtu.be/lmHomrtL4lw***.
- Interactive guide to integrated finance in geothermal energy: The tool supports the decision for the best alternative finance and risk mitigation schemes for each geothermal project. It is a self-assessment tool focused on the financial aspect, divided in two main components. On the front page, users have access to a sequence of steps to be considered with regards to finance and risk mitigation in a geothermal project. The second component consists of an interactive step plan in which users are asked a set of questions related to each of the steps and insert their answers in the respective text boxes. Once the interactive guide is concluded, users can download a report containing a full summary of their situation, with valuable information that can be used as source material for specialised consultancy, for example, to implement their projects. Link for tutorial: ***https://youtu.be/7x5ZHIhL3gs***.
- Toolbox for risk evaluation and mitigation: The tool addresses the economic modelling for each geothermal project. It is a technical tool that was prepared to help geothermal project developers to efficiently perform economic modelling of their projects, also divided in two levels. The front page contains an overview about the toolbox and the list of the necessary

Table 1: Summary of the Core Services.

Service	***For whom***	***What?***
Decision support tool	*Project developers & Local authorities*	*Offering a workflow with questions on social, environmental, financial, and risk mitigation factors to help you identify appropriate strategies for your project.*
Interactive guide to integrated finance in geothermal energy	*Community investors & project developers*	*A self-assessment with regards to the financial and risk mitigation framework to consider in developing a geothermal project, according to the profile of your community.*
Toolbox for risk evaluation and mitigation	*Project developers*	*Parameters to help you perform complete economic modelling of geothermal projects, with or without community funding.*
Implementation framework for community-based geothermal development	*Community investors & project developers*	*Five fundamental aspects to consider for any geothermal energy project developed by a community of citizens.*
Information catalogue for self-learning	*Community investors & geothermal professionals*	*Offering in-depth information on anything related to the CROWDTHERMAL pillars: community financing, social aspects, risk mitigation and geothermal energy.*
FAQ	*Community investors*	*Answers to all of your questions around community financing for geothermal projects, social engagement strategies, risk mitigation and geothermal energy.*
Meta-database of geothermal projects	*Community investors, project developers & local authorities*	*Your platform of geothermal projects that are potentially suitable for alternative financing schemes.*

parameters to calculate the costs of a geothermal project, for project description, geology & heat power plant, CAPEX, OPEX, and financing plan. The main part of the tool is a downloadable spreadsheet in which all parameters are included, and project developers can enter their actual numbers for each of them. Upon completion of the spreadsheet, users will have a complete summary of their costs at their hands – which will help them in preparing an economic model of their project, with or without help from external consultants. Link for tutorial: ***https://youtu.be/1J4XWXIcigo.***

- Implementation framework for community-based geothermal development: The key elements to be taken into consideration for the development of community to finance geothermal projects are presented in this tool. It is a report that compiles five fundamental aspects that should be taken into consideration when implementing a geothermal project, based on CROWDTHERMAL case studies that were concluded in Spain, Hungary and Iceland: a) characterization of the project, b) social aspects, c) regulatory framework, d) innovative finance mechanisms, and e) financial risks in a geothermal project. The report is interactive and its navigation is facilitated through the table of contents and additional functions to improve the users' experience. Link for tutorial: ***https://youtu.be/0XwTNEZTSE4.***
- Meta-database of geothermal projects: The tool aims to connect users with services. Geothermal projects with the potential for alternative finance, risk mitigation and social engagements have been identified by EFG's National Associations in Europe and included in the database. The database also informs visitors about the national geothermal framework of European countries, existing geothermal projects, including benchmark projects, and provides the option to self-register in the database to facilitate networking with other project developers and learn about how other projects benefit from alternative finance. There are two maps created, using the data from the country overview and the geothermal projects, as a map-based search engine. The primary user for this tool are project developers. The data collection is ongoing and the meta database is open for new registrations. Link for tutorial: ***https://youtu.be/HizzIXiiBpk.***
- Education tools: Finally, there are educational Core Services in the portal dedicated to all CROWDTHERMAL stakeholders who wish to learn more about its key topics. For example, communities of investors who are not familiar with geothermal energy, or project developers who are not aware of the benefits of alternative finance. First, the 'Information Catalog for Self-learning' consists of wiki articles that explain common topics related to CROWDTHERMAL pillars, such as social aspects, alternative finance, risk mitigation and geothermal energy. Similarly, the 'Frequently Asked Questions' provide shorter explanations and key references for further research. Link for tutorials: ***https://www.youtube.com/watch?v=2vVjnyIJcfo.***

The CROWDTHERMAL tools and added value to its target audiences are summarised in Table 1 based on data from [7, 8, 9, 10, 11].

3. Conclusions

We are at a historic moment in terms of the need to use renewable energy. Geothermal energy remains a largely underused power source in the overall energy mix in Europe. Therefore, the CROWDTHERMAL project aims to empower citizens and local communities for local clean energy solutions, contributing to the European Green Deal.

Geothermal energy is a resource that has a large potential for further deployment and development in many countries around the world. In Europe, the status of geothermal deployment ranges from direct use of hydrothermal resources in sedimentary basins, or high-temperature geothermal resources found in volcanic areas, to shallow and low-temperature geothermal.

In order to enhance the presence of geothermal projects in the mix of renewable energy sources in Europe, the multidisciplinary team of CROWDTHERMAL research combines engineering and technical knowledge on geothermal energy with social science, psychology, innovative finance engineering and social innovation. This interdisciplinary combination of expertise has resulted in the development of a set of key project outcomes, shared and converted into web tools – the CROWDTHERMAL Core Services.

The analysis in this project confirms that co-financing, co-ownership, and shared responsibility all support the energy transition, as they extend the possibilities of social acceptance. Alternative finance has the double potential of co-funding the project and involving citizens in the development of the project. The implementation of the techniques of alternative finance requires an analysis of the attitudes and preferences of the local community. The project described in this article presents guidelines for this type of analysis.

The specific financial risks inherent to geothermal installations also raise barriers for investors. Part of these risks are related to the resource uncertainties; others are related to the probability of achieving social acceptance. The project has explored mechanisms to mitigate these risks and even convert them into opportunities by applying alternative financial mechanisms.

CROWDTHERMAL provides mixed expertise to target these bottlenecks, through the development of tools adding value for project developers, local authorities and communities of citizens.

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A Risk Mitigation Framework for Community-Based Financing in Geothermal

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As part of the Horizon 2020 project CROWDTHERMAL, the opportunities of different alternative finance strategies – like crowdfunding – for geothermal projects were assessed along with their potential risks and possible mitigation measures. Recommendations were formulated for a novel Risk Mitigation Framework that can complement alternative financing solutions for deep geothermal projects throughout Europe. A support mechanism is proposed that addresses several of the main barriers to geothermal market development. It can reduce the amount of risk capital required by project developers and can help more projects become economically feasible. At the same time, it can mitigate the financial risk for community investors and broaden the applicability of participatory finance for geothermal project funding. An economic analysis was carried out confirming and quantifying these effects.

Dans le cadre du projet Horizon 2020 CROWDTHERMAL, les opportunités de stratégies de financement alternatives - comme le financement participatif - pour les projets géothermiques ont été évaluées ainsi que leurs risques potentiels et les mesures d'atténuation possibles. Des recommandations ont été formulées pour un nouveau cadre d'atténuation des risques qui peut compléter les solutions de financement alternatives pour les projets de géothermie profonde dans toute l'Europe. Un mécanisme de soutien est proposé qui s'attaque à plusieurs des principaux obstacles au développement du marché géothermique. Il peut réduire le montant de capital-risque requis par les développeurs de projets et peut aider davantage de projets à devenir économiquement réalisables. En même temps, cela peut atténuer le risque financier pour les investisseurs communautaires et élargir l'applicabilité de la finance participative pour le financement de projets géothermiques. Une analyse économique a été réalisée confirmant et quantifiant ces effets.

Como parte del proyecto CROWDTHERMAL de Horizonte 2020, se evaluaron las oportunidades de diferentes estrategias de financiación alternativa, como el crowdfunding, para proyectos geotérmicos junto con sus riesgos potenciales y posibles medidas de mitigación. Se formularon recomendaciones para un novedoso marco de mitigación de riesgos que puede complementar soluciones financieras alternativas para proyectos geotérmicos profundos en toda Europa. Se propone un mecanismo de apoyo que aborda varias de los principales obstáculos para el desarrollo del mercado geotérmico. Este novedoso marco de mitigación de riesgo, puede reducir la cantidad de capital de riesgo requerido por los desarrolladores de proyectos y puede ayudar a que más proyectos sean económicamente viables. Al mismo tiempo, puede mitigar el riesgo financiero para los inversores comunitarios y ampliar la aplicabilidad de las finanzas participativas para la financiación de proyectos geotérmicos. Se realizó un análisis económico confirmando y cuantificando de estos efectos.

1. Introduction

Despite its enormous potential to supply sustainable, decentralised, and low-carbon baseload energy for electricity, heating, and cooling purposes, deep geothermal still plays a marginal role in the European energy mix. The high resource risk that is typically present in the early stages of geothermal project development makes it difficult to mobilise the required capital for funding early exploration surveys and first drillings through traditional bank finance.

The exploration risk – the risk of not finding a geothermal reservoir in sufficient quality or quantity for economically viable exploitation – significantly contributes to the investment reluctance and the relatively slow development of the deep geothermal industry. In order to realise investments in geothermal, it is necessary to provide sufficient investment security by mitigating the exploration risk [1,2]. Several de-risking and insurance schemes with different regional foci and various risk-sharing concepts have been established or are currently being developed internationally to address this issue [3-5].

So far, however, none of the existing or envisaged schemes allows for combining risk mitigation and community funding for geothermal projects. Yet, alternative finance methods like crowdfunding can be vital elements of the funding plan for deep geothermal projects. They can close the financing gap and reduce the amount of equity required for early project phases. At the same time, they can improve local project ownership and mitigate the risk of project failure due to non-acceptance [6,7].

New approaches to participatory finance for geothermal also bring about new scopes of risks. Community investors in geothermal projects basically face the same exploration risk as project developers. Unless the investment is secured by a guarantee or insurance scheme, crowd investors risk losing (part of) their money in case of project failure. If geothermal crowdfunding is to be applied more widely, an accompanying mechanism is needed that can reduce the exploration risk exposure of community investors to a proportion that they can absorb.

Against this background, one of the main objectives of the project CROWDTHERMAL was the development of a conceptual framework for a risk mitigation scheme that can complement alternative financing solutions for geothermal projects throughout Europe.

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2. Methodology

The groundwork for this task was laid by a demand analysis for geothermal risk mitigation in which we performed a cluster analysis amongst various stakeholders [8]. More than 30 networking dialogues were established with geothermal project developers, investors, co-operatives, past and ongoing exploration risk mitigation schemes and initiatives, the insurance market, geothermal and institutional experts, research projects, geothermal energy policy initiatives, and public authorities. In-depth interviews were held with risk mitigation experts from several organisations and programmes experienced in geothermal risk mitigation (namely the World Bank Group, GRMF, ARGeo, KfW, and the BGR-GEOTHERM programme). The interviews focused on lessons learned from previous geothermal de-risking schemes and as of yet unaddressed issues in risk mitigation. A questionnaire on risk assessment and risk mitigation demand was filled in by the CROWDTHERMAL Case Studies Szeged (Hungary), Madrid (Spain) and Húsavík (Iceland). Finally, additional interviews were held with two German projects that experienced project failure due to an unsuccessful well (Offenbach/Queich and Geretsried) in order to get an understanding of different facets of risk materialisation.

Drawing upon several cases where alternative finance solutions had already been applied in geothermal projects, we next analysed various alternative financing methods about their key advantages, potential risks, and possible mitigation strategies, both from a project developer's and from a community investor's perspective [9]. For this purpose, we studied nine geothermal cases from France, the UK, the Netherlands (2), Spain, Iceland, Germany, Kenya and Romania as examples of different types of community funding. The cases include one negative example of financial fraud in order to demonstrate what happens when such a risk occurs and to avoid future repetition. Besides eight deep geothermal projects, the CROWDTHERMAL Case Study Madrid served as a positive example for crowdfunding for shallow geothermal developments. The results were condensed into an alternative finance risk inventory [10].

Based on the requirement specifications from the demand analysis and the results of the alternative finance risk inventory, we developed recommendations for a Risk Mitigation Framework for deep geothermal projects utilising community funding. The conceptual framework was refined in cooperation with experts from within and outside the CROWDTHERMAL consortium contributing geothermal policy, financial, crowdfunding and insurance sector expertise [11].

An economic analysis subsequently evaluated the economic implications of the proposed Risk Mitigation Framework [12]. For the economic assessment, the modelling software Renewalyzer – designed for economic calculations of geothermal and other renewable energy projects – was adapted to encompass alternative finance and risk mitigation solutions. Profit and Loss, Cash-Flow, and Balance Sheet statements were generated in order to compile and evaluate different economic benchmark parameters for a range of scenarios.

The work presented here was concluded by assessing potential financiers for the CROWDTHERMAL Risk Mitigation Fund [13]. Special attention was paid to financing institutions that have already demonstrated their interest in the geothermal or alternative finance market.

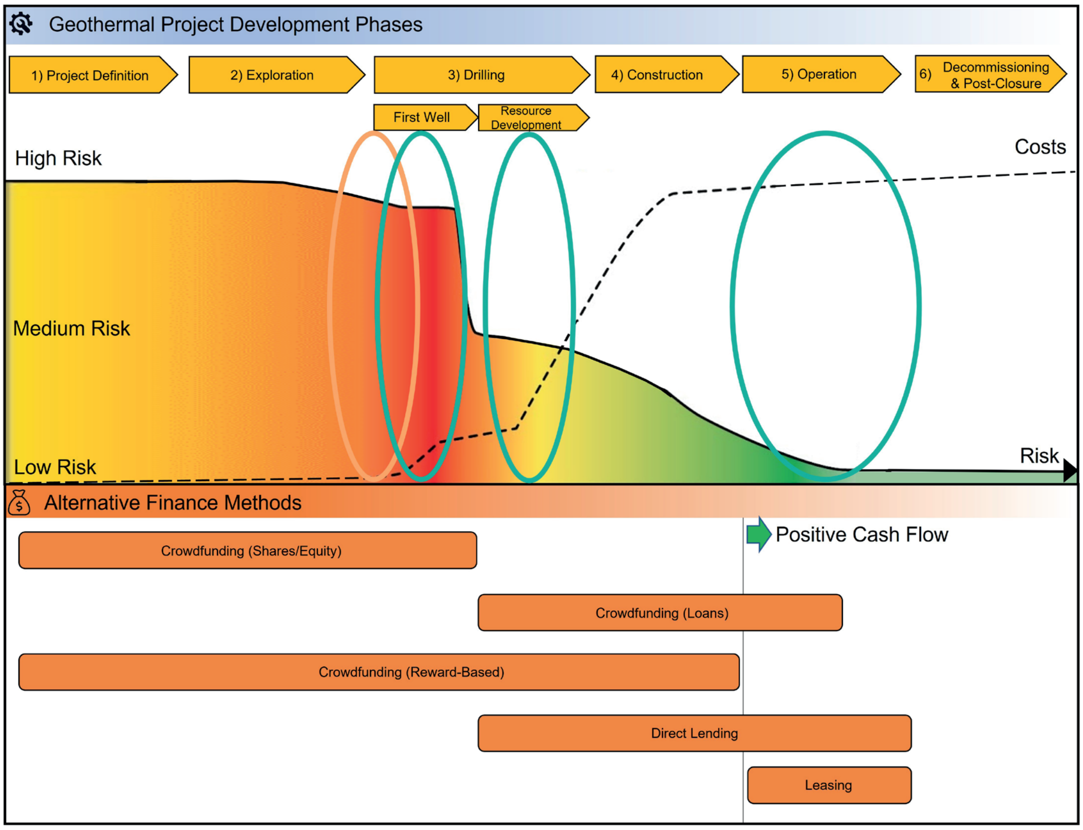

Figure 1: Technical geothermal project development phases, associated risks, costs, and most appropriate alternative finance methods. Timing of the support from the proposed CROWDTHERMAL Risk Mitigation Framework. Orange circle: co-financing support, green circles: loan guarantee range ([11], modified after [14] and [15]).

3. Results

3.1. *Alternative Finance Risk Mitigation*

The most common forms of alternative finance that can be used along the course of geothermal project development are crowdfunding (loans), crowdfunding (shares/equity), crowdfunding (reward-based), direct lending and leasing. Crowdfunding is the most commonly used form of community funding, where funds are raised from the community – often through a crowdfunding platform – in return for a set interest rate (loans), dividends (shares/equity) or rewards (reward-based). Direct lending is lending by a financial intermediary without a banking license that attracts funding and uses this funding to give out loans to other parties. A special form of direct lending is social bonds or green bonds. Such impact bonds can be given out by a project itself and are specifically earmarked to raise money for climate and environmental projects or projects that are intended to create better social outcomes. A lease is a contract that permits the use of an asset. The “lessor” purchases or develops an asset and then leases it to the “lessee” in return for a contractually agreed series of payments [9].

Successful community funding needs to match the characteristics and funding requirements of individual geothermal projects along with the community investors’ risk appetite and motivation for involvement. Before choosing a specific form of alternative finance fundraising or investment, all options along with the associated opportunities and risks should be evaluated to systematically improve risk management and decision-making processes.

As a general recommendation, it can be stated that in the early project phases, which are associated with the largest exploration risk, equity or reward-based crowdfunding instruments are often the most suitable (*Figure 1*). These instruments offer a high level of involvement for the investors, and – for the equity models – also high potential returns. They do however imply a relatively high risk of financial losses in case of project delay or failure (for example due to drilling problems or a dry well) and are therefore only suitable for community investors with a sufficient risk-absorbing capacity.

From the point in time when the geothermal resource is proven, at least by a first successful well, the risk of project failure becomes much lower. From then on, uncertainties regarding a project’s timing and results are significantly reduced, and loan-based methods like crowdfunding (loans) or direct lending can be used. They are also applicable for crowd investors with a lower risk appetite.

For project developers, direct lending and leasing are two alternative finance strategies especially suited for the late project stages. While direct lending offers the opportunity of easier access to funding than through conventional bank finance, leasing can entail the advantage that the resource risk is removed from the project developer.

3.2. *The CROWDTHERMAL Risk Mitigation Framework*

Experiences from former and current de-risking schemes led to a concept for a Risk Mitigation Framework that is designed to optimally assist community-funded deep geothermal projects throughout Europe.

Given the current geothermal market conditions in most European countries, it is recommended to set up a CROWDTHERMAL Risk Mitigation Fund that would ideally be financed by a public funding source. The fund would be a pan-European support instrument mitigating the financial risks associated with subsurface uncertainties of geothermal projects. It would be applicable to deep geothermal projects that raise a minimum of 5% of their project capital expenditures (CAPEX) from community investors through loan-based alternative financing methods (i.e., crowdfunding (loans), direct lending or impact bonds).

The proposed support framework includes a grant-based, co-financing component in the form of matchfunding and a risk-sharing component in the form of loan guarantees (*Figure 2*). The matchfunding would be paid as a grant to the project developer prior to exploration drilling. It would match the amount of funds that can be raised from the crowd (for example, if two million euros are raised through loans from community investors, the Risk Mitigation Fund will invest an equal amount, i.e. an additional two million euros).

The loan guarantees would mitigate both the short-term exploration risk in the drilling phase and the long-term subsurface risks during operation (e.g. reservoir degradation due to scaling). In case an economically viable project operation is not or no longer possible, they would secure the (partial) repayment of community investors’ loans. By addressing the resource risk in different project phases (*Figure 1*), the Risk Mitigation Framework should facilitate sustainable devel-

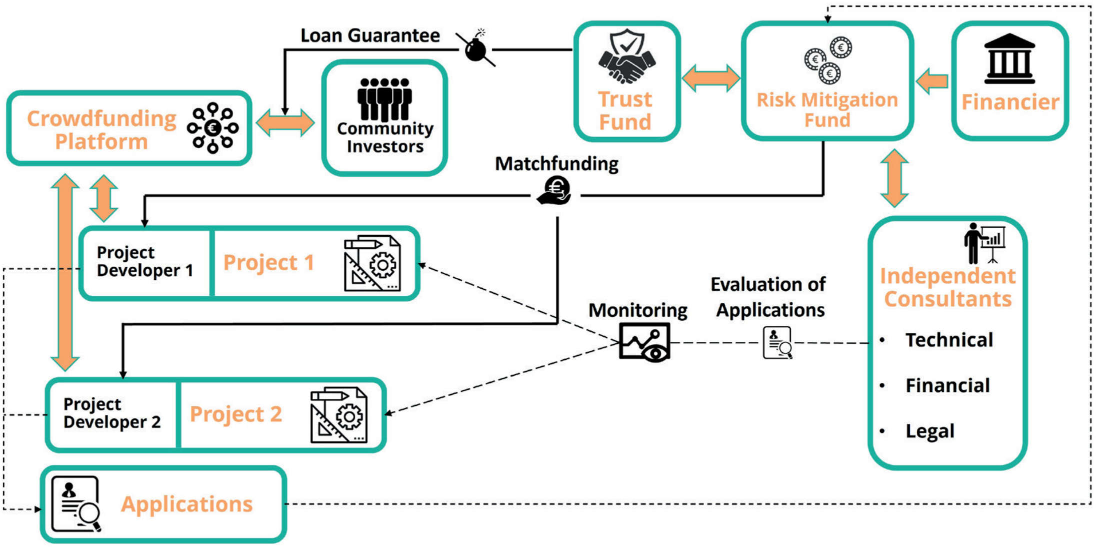

Figure 2: The Proposed CROWDTHERMAL Risk Mitigation Framework [11].

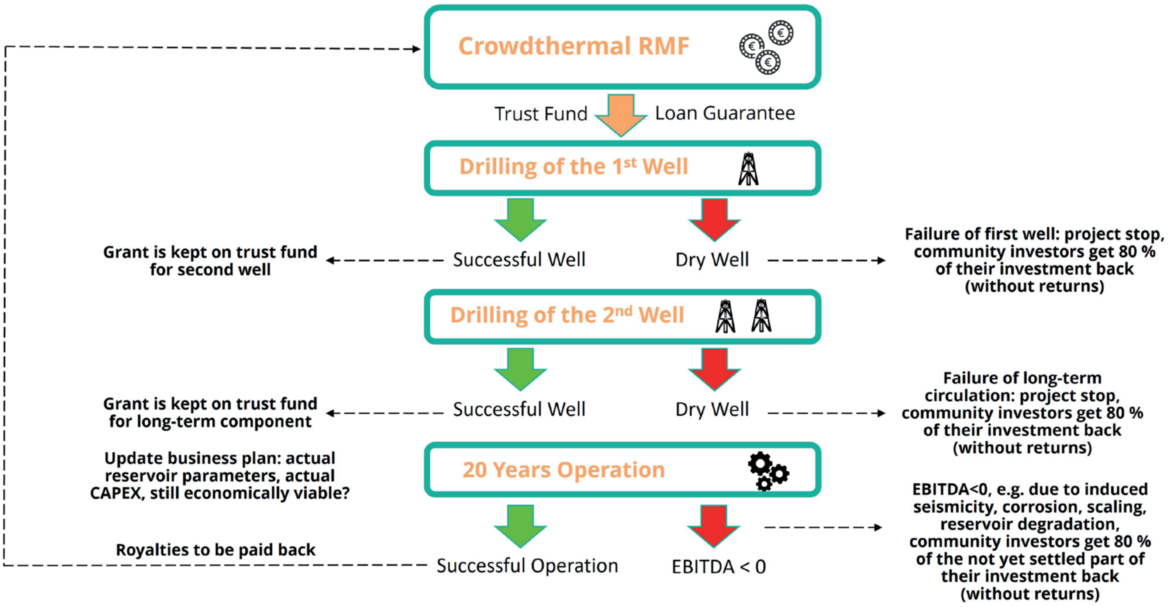
Crowdthermal RMF
Trust Fund
Loan Guarantee
Drilling of the 1st Well
Grant is kept on trust fund for second well
Successful Well
Dry Well
Failure of first well: project stop, community investors get 80 % of their investment back (without returns)
Drilling of the 2nd Well
Grant is kept on trust fund for long-term component
Successful Well
Dry Well
Failure of long-term circulation: project stop, community investors get 80 % of their investment back (without returns)
Update business plan: actual reservoir parameters, actual CAPEX, still economically viable?
20 Years Operation
EBITDA<0, e.g. due to induced seismicity, corrosion, scaling, reservoir degradation, community investors get 80 % of the not yet settled part of their investment back (without returns)
Royalties to be paid back
Successful Operation
EBITDA < 0

Figure 3: Operating Principles of the CROWDTHERMAL Risk Mitigation Fund's Short- and Long-Term Loan Guarantees [11].

opments throughout the project lifetime.

In case a loan guarantee is needed, the guarantee amount would be paid from an ear-marked Trust Fund. Payments from the Trust Fund would be made through the crowdfunding platform or financial intermediary facilitating the community funding process. This procedure ensures that the loans of community investors are not subordinated.

The decision over project success and failure should take into consideration the project-specific reservoir and economic parameters. The short-term loan guarantee would be activated in case the actual reservoir parameters do not allow an economically viable project. The decision would be made on the basis of the results after drilling, testing, and – if applicable – enhancement of the first or second well (*Figure 3*). The threshold for the long-term loan guarantee to be activated would be a negative value of a project's earnings before interest, taxes, depreciation, and amortization (EBITDA) during operation. This scenario could for example occur if induced seismicity requires additional seismological monitoring and a reduction in circulation rate. Successful projects would be required to pay back revenue-based royalties, thus making the fund both a risk- and profit-sharing facility.

The establishment and implementation of the Risk Mitigation Framework would be accompanied by an expert committee of external, independent consultants or advisors with technical, financial and legal expertise. The importance of mechanisms for alignment of interest and quality assurance is highlighted. Concrete suggestions are given in [11].

The proposed support framework tackles several of the main financial barriers to geothermal market development and offers the following benefits:

- It encourages deep geothermal project developers to apply alternative finance solutions;
- The matchfunding is an incentive for project developers for a maximum use of financial community engagement. At the same time, the matchfund is positively leveraged by the community funding;
- Providing matchfunding grants prior to exploration drilling reduces the amount of (equity) risk capital needed by project developers. The co-financing contributes to the project budget that can be used for early phases' CAPEX and helps to close the financing gap;
- With the proposed loan guarantee, the financial risk to be carried by individual community investors becomes much more predictable and acceptable. The investment will become more attractive;
- For project developers, crowdfunding is relatively costly. Due to the high-risk profile of deep geothermal projects, investors usually expect high returns. A loan guarantee reducing the risk level for community investors can entail lower return expectations to be met by project developers;
- Adding a guarantee to alternative financing loan instruments introduces more flexibility in investment opportunities in the early project phases. It also gives people with a lower appetite for risk the opportunity to be part of the project from the beginning;
- With the guarantee, the applicability of loan-based community funding solutions is broadened. The bars for the suggested application range of crowdfunding (loans) and direct lending in Figure 1 can be extended to also cover the project definition and exploration phases;
- For project developers, the guarantee helps to pay back loans in case of project failure. It considerably reduces the financial risks associated with subsurface uncertainties. Besides the focus on the exploration risk, other subsurface risks like drilling risks, corrosion, scaling, or long-term degradation of the reservoir are also captured by the proposed approach;
- The Trust Fund concept and the cooperation with platforms or financial intermediaries ensure that the loans of community investors are not subordinated;
- The loan guarantee can help to secure confidence and peace of mind for project developers, platform operators/financial intermediaries, and community investors alike;
- The scheme can help to pool geothermal projects that apply alternative finance solutions for knowledge exchange, the use of synergies, cohesion, spreading of risk, and to obtain a critical mass;
- The presented framework is appli-

cable to all Geothermal Play Types. It supports different deep geothermal project types and sizes and can equally encourage the development of low, medium, and high enthalpy resources;
- Promoting new geothermal initiatives and more sustainable energy can benefit Europe and its de-carbonisation strategies.

3.3. Economic Assessment

Once the conception of the CROWDTHERMAL Risk Mitigation Framework was worked out, economic efficiency calculations were performed in order to assess the economic implications of the framework for both project developers and community investors [12]. The assessment analysed the effects of the CROWDTHERMAL Risk Mitigation Framework on the economic feasibility, profitability, bankability, and investment risk level of a project.

In a scenario analysis, a range of quantitative and qualitative economic indicators was compiled for an array of project success and failure scenarios. The 18 scenarios were arranged in a way that they can demonstrate the individual effects of crowdfunding and matchfunding, as well as short- and long-term loan guarantees.

The benchmark parameters include both tangible figures like IRR (Internal Rate of Return) and NPV (Net Present Value) and more qualitative criteria like the investment risk level at a certain point in time. They illustrate the project perspective, the principal equity investor perspective, the bank perspective, and the community investor perspective. In their entirety, they can give indications regarding expectable investment decisions, decisions over project stop versus continuation, the economic efficiency of a project, and a project's ability to fulfil its obligations towards community investors.

The economic analysis confirmed that both community finance and each individual component of the proposed CROWDTHERMAL Risk Mitigation Framework have a positive effect on the overall economic performance of a deep geothermal project. The application of the Risk Mitigation Framework can entail more positive investment decisions and encourage more project continuations. It can help more projects become economically feasible and can improve a project's bankability. It has a positive effect on the ability to repay loans and reduces the risk of insolvency and project stop. For community investors, the framework reduces the amount of capital at risk as well as the risk of credit default and losses, thus making geothermal a safer investment.

3.4. Sponsorship

Obviously, the largest challenge for initiatives like the CROWDTHERMAL Risk Mitigation Fund is to find a financier providing the required seed capital for its establishment.

A potential financier of the proposed CROWDTHERMAL Risk Mitigation Fund needs to have the willingness and ability to provide funds to a support scheme for relatively high-risk projects without expecting a direct return on investment. The motivation would rather be a return on impact: to support the market uptake of community-funded geothermal projects in Europe with all associated benefits for the environment and for society. An overview of various potential funding sources and sponsors from different public and private investor categories is given in [13].

In the light of the deep geothermal market status in Europe, high involvement of public aid-granting entities is considered important [16]. Ideal funding sources hence include transnational financing bodies, development banks, national governments, and public investment funds. At the EU level, a wide range of public financing instruments already offer funding opportunities for renewable energy initiatives. The European Green Deal for climate neutrality by 2050 and the REPowerEU plan introduced in May 2022 have set the stage for a multitude of additional funding opportunities for low-carbon energy technologies. New strategies for de-risking renewable energy projects have also emerged from the Renewable Energy Directive recast process. Unlocking such funds to finance a geothermal risk mitigation scheme would be a great chance to advance the geothermal sector.

Besides public funding, results-based green financing through social bonds, green bonds, private financing institutions, or strategic investors can be additional sources of capital for the CROWDTHERMAL Risk Mitigation Fund. Several oil and gas players, for instance, have committed to climate neutrality in the future and are converting their companies and business structures accordingly. Likewise, utility companies and energy providers are increasingly attentive towards alternative energy sources for the green energy transition. Furthermore, insurance companies are interested in geothermal as a technology that can help reduce claims related to climate change. In individual cases, tangible experience with geothermal and/or crowdfunding complements the strategic interest of such private market players.

The crowdfunding ecosystem has already proven the legal and operational feasibility of co-funding and risk-sharing collaborations between public entities and community-funded projects, for example in the framework of the European Structural and Investment Funds (ESIF) [17]. In addition, the European crowdfunding regulation (ECSP) adopted in late 2021 provides a common structure and harmonised framework and is expected to boost the European crowdfunding industry in the coming years. Against this background, now is a very favourable moment to establish a Risk Mitigation Fund for geothermal crowdfunding in Europe.

4. Discussion

A novel Risk Mitigation Framework is presented that addresses the exploration risk of community-based geothermal development schemes. It is a tailored derisking scheme that considers the needs of both geothermal and alternative finance industry, of both project developers and community investors. It is a relevant concept, designed to optimally assist community-funded deep geothermal projects and to encourage public participation in geothermal funding. Once implemented, it can be an effective way to assist the geothermal sector and to facilitate European market development.

An economic analysis confirmed that the conceptual CROWDTHERMAL Risk Mitigation Framework can achieve a significant reduction of the main economic challenges and risks that are faced by deep geothermal project developers and community investors:

- It tackles the lack of risk capital for geothermal developments;
- It facilitates public participation in geothermal projects;
- It complements alternative finance solutions;
- It protects community investors‘ interest;
- It mitigates the exploration risk.

To be able to reach its objectives, the support scheme first needs to be funded and established. The existence of various public and private financing options has been demonstrated. A multitude of further funding opportunities are expected to emerge in the wake of recent policy priorities and initiatives. The newly adopted pan-European crowdfunding directive has additionally set the stage for remarkable growth of the European alternative finance market.

Against this background, now is the perfect time to gain momentum in community investments in geothermal projects. Finding a sponsor to implement the CROWDTHERMAL Risk Mitigation Fund can be an important stepping stone for the geothermal industry to seize the present opportunities and to progress towards fulfilling its great potential.

Political support at all levels remains crucial, both regarding the public funding of geothermal de-risking schemes and regarding the enforcement of decarbonisation efforts so that strategic investments in geothermal become sufficiently appealing.

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Public perceptions of geothermal projects: New ways of measuring and monitoring local acceptance and social impacts

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For a successful energy transition, the deployment of renewable energy sources like geothermal is a fundamental step towards a sustainable power and heat production. In this context, public acceptance towards such energy projects is a crucial factor for both the number of realised projects and the speed of their realisation. Based on empirical work, the paper discusses the factors relevant for the acceptance of geothermal projects and provides an insight into new approaches for measuring acceptance and social impacts connected with geothermal projects within the conceptual frame of social license to operate. The presented approach serves as a guiding tool for public engagement as well as an instrument for monitoring acceptance and social impacts. Therefore, the paper feeds both the scientific discourse and practical applications.

Pour une transition énergétique réussie, le déploiement des énergies renouvelables comme la géothermie est une étape fondamentale vers une production durable d'électricité et de chaleur. Dans ce contexte, l'acceptation du public envers de tels projets énergétiques est un facteur crucial tant pour le nombre de projets réalisés que pour la rapidité de leur réalisation. Sur la base de travaux empiriques, cet article examine les facteurs pertinents pour l'acceptation des projets géothermiques et donne un aperçu de nouvelles approches pour mesurer l'acceptation et les impacts sociaux liés aux projets géothermiques dans le cadre conceptuel de la licence sociale d'exploitation. L'approche présentée sert d'outil d'orientation pour l'engagement du public ainsi qu'un instrument de suivi de l'acceptation et des impacts sociaux. Ainsi, l'article alimente à la fois le discours scientifique et les applications pratiques.

Para una transición energética exitosa, el despliegue de fuentes de energía renovables como la geotérmica es un paso fundamental hacia una producción de energía y calor sostenible. En este contexto, la aceptación pública de dichos proyectos energéticos es un factor crucial tanto para el número de proyectos realizados como para la velocidad de su realización. Con base en resultados empírico, este trabajo analiza los factores relevantes para la aceptación de proyectos geotérmicos y proporciona una idea de los nuevos enfoques para medir la aceptación y los impactos sociales relacionados con los proyectos geotérmicos dentro del marco conceptual de la licencia social para operar. El enfoque presentado sirve como una herramienta de orientación para la participación pública, así como un instrumento para monitorear la aceptación y los impactos sociales. Por lo tanto, el artículo alimenta tanto el discurso científico como las aplicaciones prácticas.

1. Introduction

The development of new energy infrastructural projects such as geothermal energy projects ought to be observed under the perspective of a sociotechnical system approach, which means that each installed technological object is not just a technical matter, but rather very much a question of social and economic change with impact on people's everyday lives regarding energy production, distribution and consumption. In this context, the various renewable energy projects also repeatedly have had to contend with acceptance problems at the local level during recent decades. Many studies show a wide range of different acceptance factors that are relevant in this context: changes to the landscape, fear of negative effects on the environment, nature or one's own health, and planning and approval procedures that are experienced as unfair or non-transparent [1]. In the context of deep geothermal plants, fear of earthquakes triggered by drilling is also a specific acceptance factor [2]. In the past, there have been several studies on the acceptance of geothermal energy projects as challenges for public acceptability in different countries [3–7]. It has become evident that, in addition to the factors mentioned above, communication and participation as means to address the perspectives of different stakeholder groups and laypersons within the public, play a crucial role in acceptance [8,9].

In this context, the importance of including the public in the development and installation of new energy infrastructure has been increasingly recognised in recent projects as well as in the literature [10–12]. According to Rowe and Frewer [13], public participation is "the practice of involving members of the public in the agenda-setting, decision-making, and policy-forming activities of organizations/institutions responsible for policy development" [p. 252]. In the context of geothermal energy projects, a distinction can be made between the involvement of people on the participatory side, usually politics or the project management,

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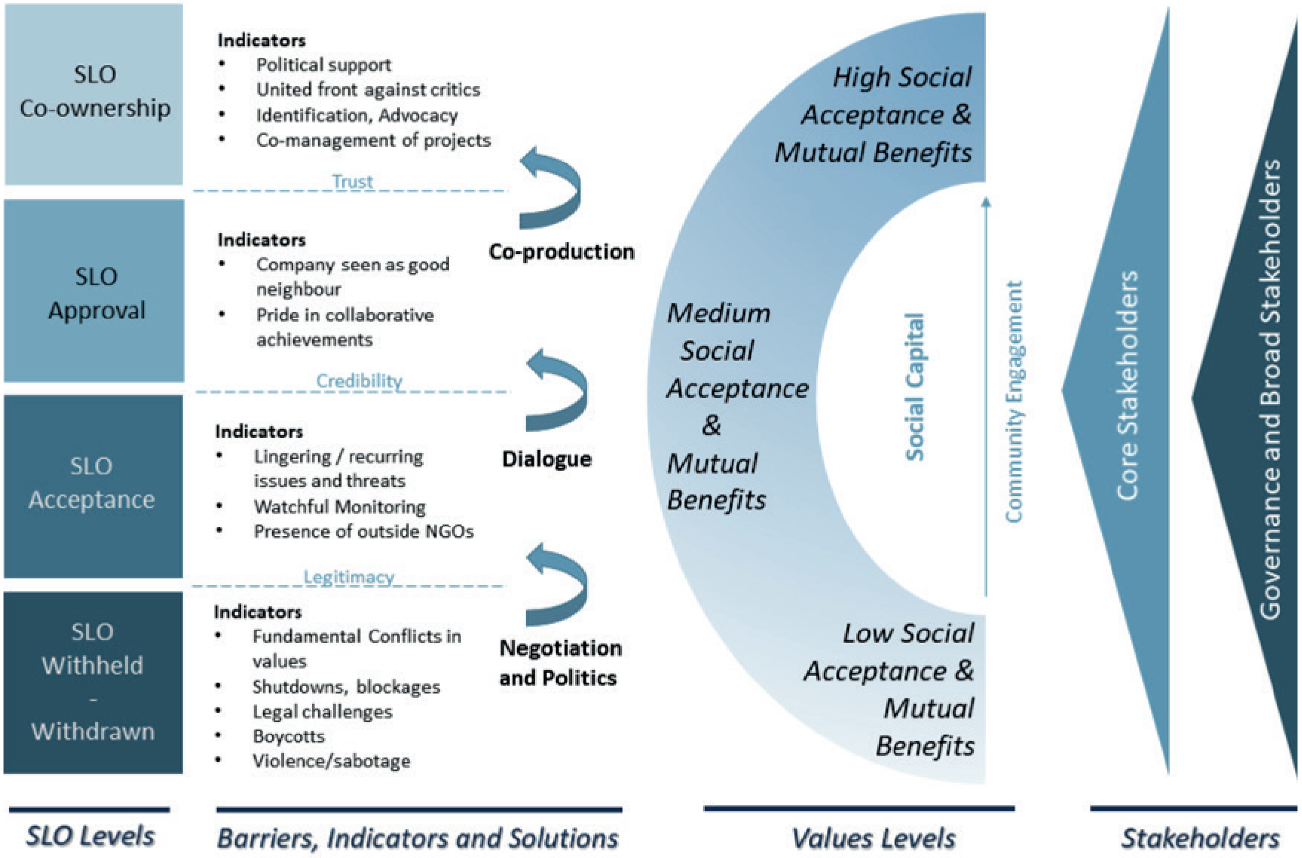

Figure 1: Conceptual framework of social license to operate (SLO) in geothermal energy [14, p. 12]. See text for details.

and the side of the participants, mostly referred to as the public or citizens. Participation means information exchange between members of the public and members of the project, usually taking place in the context of planning and permitting procedures. Ideally, it will lead to a negotiation that mutually influences and transforms the opinions and agendas of members of both the public and project-related parties. The more decision-making power is redistributed and shifted towards the citizens, the more genuine and successful participation can be.

Following these considerations on participation, the conceptual approach of a Social License to Operate (SLO) goes beyond participation in planning and approval processes. This approach not only integrates different levels of acceptance, barriers, and indicators, but also allows for the consideration of the temporal dimension and context dependency. In ***Figure 1***, the main components of the SLO model are shown. The figure shows that at the highest SLO level, the level of co-ownership, the energy project is part of the local identity and people feel advocacy for the project [14]. Likewise, well-known relevant factors for approval and acceptance are integrated in the model, such as trust, mutual respect, dialogue, and transparency providing a high degree of procedural justice [15, 16]. Thus, the SLO concept strongly relates to corporate social responsibility and provides an approach for a comprehensive understanding of the co-existence of businesses and people within a community based on the development of strong relationships.

This paper examines the extent to which the constructs integrated in the SLO model can be empirically proven. Specifically, three main research questions are addressed: the first research question concerns the operationalisation of the variables in the SLO model; here it is assumed that the scales measuring the variables have both a good fit and are significantly related to each other, corresponding to their theoretically assumed role in the SLO model. The second is the prediction of local acceptance using the constructs represented in the model, and the third is the investigation of the factors influencing the identification with the local project in terms of perceived co-ownership as the highest level of SLO.

2. Materials and Methods

In order to examine the approach including relevant factors for the acceptance of geothermal projects, acceptance levels and social impacts connected with geothermal projects within the frame of social license to operate, empirical work was conducted for different case studies. In the following sections, the project background, methodological approach and results are presented in the socio-economic context of Hungary.

Case study: project background and methodological approach

A total of 27 geothermal wells (9 production and 18 injection wells) are being constructed, whereby the supply of 26,338 end users (of the 27,257 total) will be based on renewable energy in the city of Szeged, Hungary. This geothermal energy project, facilitated by the District Heating Company of Szeged, started on September 26th, 2017. Since then, the project has been in constant progress. Nine projects targeting multiple heating circuits have received EU funding and work has either started or

Table 1: Overview and characteristics of the scales used in the questionnaire.

Scale name	*Number of Items*	*Mean value*	*Standard deviation*	*Reliability α*
General acceptance of renewable energy systems (RES)	*5*	*4.64*	*0.68*	*0.95*
Local acceptance of geothermal energy	*3*	*4.66*	*0.64*	*0.94*
Perception of benefits of geothermal energy	*4*	*4.10*	*0.92*	*0.92*
Risk perception	*4*	*2.73*	*0.95*	*0.74*
Annoyance perception towards geothermal energy	*3*	*2.43*	*1.02*	*0.82*
Trust attribution towards the developing company	*10*	*3.62*	*1.06*	*0.98*
Procedural justice perception	*8*	*2.44*	*0.77*	*0.95*
Impact on the social structures of the community	*7*	*3.13*	*1.01*	*0.98*
Association of the geothermal project with local identity	*4*	*3.13*	*1.13*	*0.96*

Table 2: Descriptive results of the scale 'Local Acceptance of Geothermal Energy'

	Generally, I support geothermal energy.	***Geothermal energy should play an important role in future power generation.***	***I would support a geothermal energy project near my home.***
Responses (n = 287)	*277*	*276*	*275*
*Mean**	*4.67*	*4.68*	*4.56*
Std. Deviation (SD)	*0.66*	*0.66*	*0.85*

**The Mean value was calculated on the base of a 1-5 Likert rating scale, ranging from 1 - totally disagree to 5 – totally agree.*

will start soon [17].

A total of 27 geothermic well systems are being constructed, servicing 9 heater loops on the basis of renewable energy. With about 96% of end-users affected, it is going to be the second largest geothermal district heating system in Europe following Reykjavik. The potential of and interest in the thermal energy in the area are linked to the fact that the geothermal gradient in the Pannonian Basin is the highest in Europe after Iceland. As space heating is considered a main use of energy by households, it is expected that with the help of deep geothermal energy, a total of nearly 20 million m^3 of natural gas will be replaced with 600,000 GJ of geothermal energy per annum, reducing the greenhouse gas load of the city of Szeged by 35,000 tons/year, improving air quality and security of supply. Geothermal energy in the district heating will result in saving 595,887 GJ/year (82%) or 17,525,718 m^3/year (68%) of natural gas and will provide 536,298 GJ/year thermal energy in district heating and 34,699 t/year (65%) CO^2 emission savings.Furthermore, the geothermal project in Szeged will result in major steps towards Hungary's independence from gas imports due to the local production of thermal water. The construction started in 2019 and is expected to end towards the end of 2023. In December 2022, there were 4 systems in operation, 2 were being constructed and 3 remained for 2023.

A standardised questionnaire was constructed to capture the various constructs included in the SLO model. Based on theories and results of previous studies [18-20] on the acceptance of renewable energies, the following main scales (***Table 1***) were integrated. All scales consist of several items addressing the respective scale content and achieved satisfactory (risk perception, 0.74) to very good values (> 0.90) for Cronbach's alpha (α) as a statistical reliability measure for internal consistency of the questionnaire scales used [21].

Additionally, aspects, such as conceptual associations with geothermal energy, knowledge gained through the geothermal project, and participation intentions for the future were queried. The complete questionnaire is provided in the Appendix as supplementary material.

The survey was conducted online from June to August 2022 and was supported by the local district heating network company, which forwarded the survey link to residents using also the distribution channels within the customers of the heating network. The usual request for socio-demographic variables to control the sample, such as age and gender, was deliberately omitted to ensure maximum anonymity.

The questionnaire was designed in the national language, Hungarian, and the results were translated into English for publication. All in all, the sample for further analyses consists of 287 respondents.

3. Results

The following section provides the description of the results, following the main research questions of acceptance levels and relevant influencing factors, as well as insights into the constructs used in the SLO approach in connection with the local geothermal project.

3.1. Local acceptance levels

As a first step, the descriptive analyses on the scales used were conducted. Table 2 shows the results for the scale on Local Acceptance. With mean values above 4.5 (in a rating scale range from 1 – totally disagree to 5 – totally agree) for each of the three items (Generally, I support geothermal energy; Geothermal energy should play an important role in future power generation; I would support a geothermal energy project near my home.) it becomes evident that the acceptance level towards the current geothermal project is rather high. The standard deviation for the item "I would support a geothermal energy project near my home" is higher than the two other items, which indicates that there is a certain amount of people with lower support for the local project. Nevertheless, with a mean value of 4.56 it is still on a high level of acceptance.

3.2. Correlation among the relevant influencing factors

With the aim of examining the extent to which the constructs integrated in the SLO model are interrelated, a correlation analysis was conducted. The results in ***Table 3*** show that the individual components correlate highly significantly with each other. Referring to the formulated first research question, perceived risks and annoyances have a negative correlation: the more strongly they are perceived, the lower the level of acceptance. In addition, the analysis provides information about

Table 3: Correlation matrix of the used main scales.

Variable	*Local Acceptance*	*RES Acceptance*	*Benefits*	*Procedural Justice*	*Trust*	*Social Impact*	*Identity*	*Risk Perception*
1. Local Acceptance	*—*							
2. Acceptance RES	*0.75***	*—*						
3. Benefits	*0.68***	*0.63***	*—*					
4. Procedural Justice	*0.60***	*0.46***	*0.71***	*—*				
5. Trust	*0.56***	*0.46***	*0.67***	*0.91***	*—*			
6. Social Impact	*0.47***	*0.44***	*0.70***	*0.79***	*0.76***	*—*		
7. Identity	*0.48***	*0.36***	*0.65***	*0.75***	*0.73***	*0.80***	*—*	
8. Risk Perception	*-0.26***	*-0.20**	*-0.29***	*-0.29**	*-0.30**	*-0.19**	*-0.16*	*—*
9. Annoyance	*-0.43***	*-0.34***	*-0.46***	*-0.52***	*-0.52***	*-0.41***	*-0.45***	*0.44***

***Significant at the < 0.001 level. *Significant at the < 0.05 level. RES: Renewable Energy Systems*

Table 4: Linear least-squares regression on Local Acceptance.

Regression model on Local Acceptance				
Model	***Standard Error***	***Standardized β***	***t***	***p***
(Intercept)	*0.47*		*-1.06*	*0.291*
RES Acceptance**	***0.10***	***0.55***	***7.41***	***< .001***
Benefits**	***0.08***	***0.37***	***4.09***	***< .001***
Procedural Justice	*0.16*	*-0.24*	*-1.73*	*0.087*
Annoyance	*0.05*	*-0.00*	*-0.13*	*0.890*
Trust*	***0.11***	***0.30***	***2.23***	***0.028***

*Method: Enter. Adj. R2 = 0.78 RMSE =0.41, **Significant on level < 0.001 *Significant on level < 0.0*

Table 5: Results of the linear regression testing the predictive impact on Local Identity

Regression model on Local Identity				
Model	***Standard Error***	***Standardized β***	***t***	***p***
(Intercept)	*0.61*		*0.44*	*0.658*
Local Acceptance	*0.16*	*0.10*	*0.81*	*0.416*
Benefits	*0.18*	*-0.00*	*-0.00*	*0.993*
Annoyance	*0.08*	*-0.02*	*-0.28*	*0.778*
Procedural Justice	*0.32*	*0.29*	*1.27*	*0.208*
Trust	*0.19*	*0.03*	*0.18*	*0.854*
*Social Impact**	*0.14*	*0.44*	*2.84*	*0.006*

*Method: Enter. Adj. R2 = 0.64 RMSE =0.633 **Significant on a level < 0.001 *Significant on a level <0 .05*

the broader data structure. For example, Trust and Procedural Justice are almost completely correlated at 0.91 (the maximum would be 1 for a perfect correlation), which is an indicator that they can also be considered as one common factor.

3.3. Prediction of local acceptance and of integration in the local identity

In order to investigate which of the various factors have the strongest influence on Local Acceptance, a linear regression was performed. The results in ***Table 4*** show the strongest influence for the factors general Acceptance of Renewable Energy Systems (RES) with a standardised regression weight beta of .55 and perception of local Benefits with a beta of .37. The standardised regression weight beta (β) is normed to the range of -1 to 1; the higher it is the stronger its predictive power.

The results of the regression analysis show that respondents who are convinced about the expansion of renewable energy and also see positive effects, such as value creation or other benefits, are more likely to accept the local geothermal project. Likewise, the factor Trust with a beta of .30 is a significant predictor, which underlines the special role of trust towards the operating company. The other factors did not reach statistical significance in this test, remaining above the threshold of 0.05.

The result that Procedural Justice has a negative correlation with Local Acceptance (beta of -0.24) is contrary to the theoretical assumption of the positive effect of Procedural Justice on acceptance and also to the results of the correlation analysis (***Table 3***). This could be a statistical suppressor effect with the Trust variable, as these two scales are very highly correlated with each other (***Table 3***) [15]. This will be the subject of further analysis.

Following the SLO approach illustrated in ***Figure 1***, the integration into the Local Identity is the highest SLO level in terms of co-ownership and advocacy. Using a linear regression analysis, it was examined which factors influence and statistically predict Local Identity as a dependent variable. The results are shown in ***Table 5***.

The results of the regression analysis shown in ***Table 5*** illustrate that the perception of Social Impacts is the strongest predictor, with a significant beta of .44 and the only factor gaining statistical significance (< 0.05). The scale Social

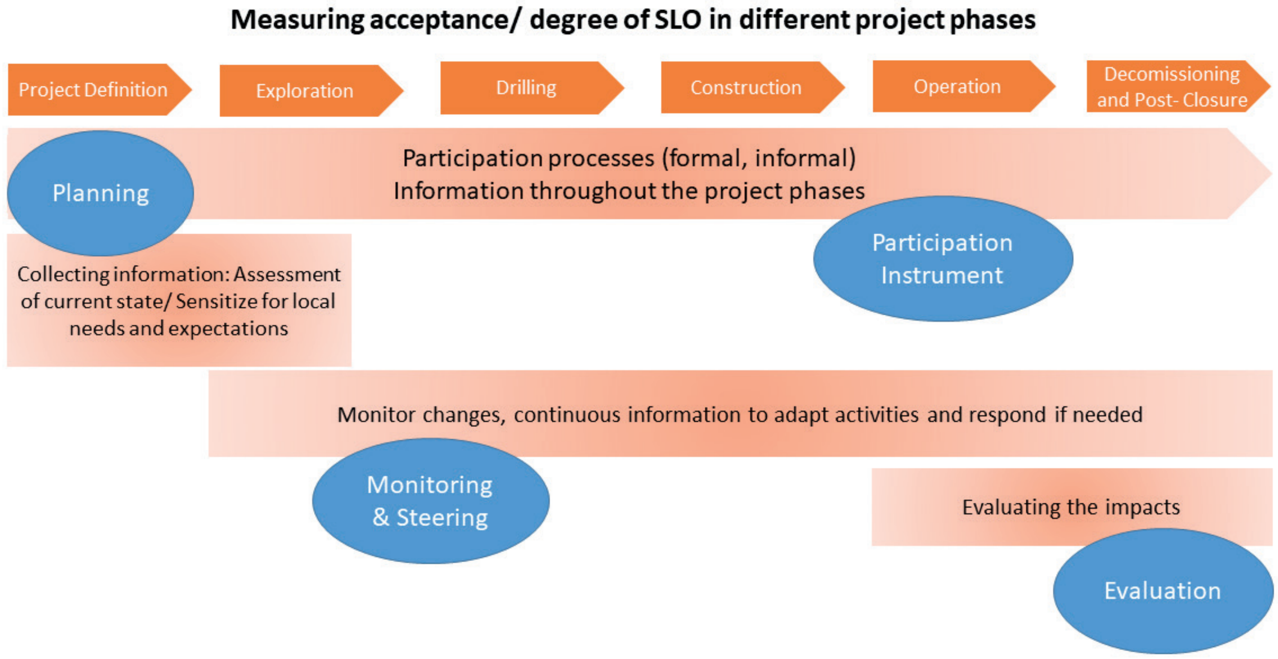
Measuring acceptance/ degree of SLO in different project phases
Project Definition
Exploration
Drilling
Construction
Operation
Decomissioning and Post- Closure
Participation processes (formal, informal)
Information throughout the project phases
Planning
Participation Instrument
Collecting information: Assessment of current state/ Sensitize for local needs and expectations
Monitor changes, continuous information to adapt activities and respond if needed
Monitoring & Steering
Evaluating the impacts
Evaluation

Figure 2: Measuring acceptance of SLO in different project phases [26]. See text for details.

Impacts includes items on the perceived positive effects on community cohesion, neighbourhood connections, or the feeling of belonging and togetherness in the neighbourhood. Thus, this result underlines that the more a geothermal project contributes to social benefits, the more it is perceived to be part of the community's self-image and the more strongly people integrate it in the community's identity.

4. Discussion

The results show that the local acceptance of the geothermal project in the case study under investigation is on a high level, which is not a matter of course for a geothermal project of this size. In the last two years, many boreholes have been drilled, causing at least temporary inconvenience to local residents. Apparently, the accompanying information and communication measures by the operating company have had a positive effect, so that in the end a positive local attitude toward the project prevails.

Regarding the influencing factors statistically predicting local acceptance in the conducted regression analysis, in particular the assumed support of renewable energy as a general attitude and the locally perceived benefits are the most important predictors (shown by ***Table 3***). This finding is in line with the results of other studies in the field of renewable energy [23–25] and shows that a multi-level strategy is necessary for the acceptable design of renewable energy deployment. On the one hand, the big picture about the goals and background of the energy transition and the role of the individual renewable technologies must be drawn and adequately communicated so that it is comprehensible and understandable to the public. Additionally, visible benefits need to be created locally for the directly affected residents, on the other hand. These benefits need not only to be of an economic or material nature, but can also manifest themselves in positive effects on the social structure of the community.

In this respect, the analyses on identity have shown that for the perceived connection and local integration of the project, the perceived social impacts, such as positive effects on social cohesion, are the most important factor. This shows the added value of the holistic SLO approach, which also includes these aspects and represents a significant advantage as an explanatory approach and monitoring tool in terms of decentralization, opportunities for participation and developments over time.

Regarding a methodological reflection on the all in all very positive perceptions of geothermal energy within the sample, it is fair to consider that this might be connected to the increased salience of the topic energy due to the war Russia started against Ukraine in February 2022. As the data collection took place in summer 2022, it can be assumed that the awareness within the population regarding the importance of independence from Russian gas for the security of supply had risen, thus a positive impact towards the acceptance of local energy projects seems reasonable.

In addition to the scientific results presented above, the SLO concept can play a role when it comes to practical implementation of geothermal projects. The SLO concept and the corresponding standardised protocol can be used with different functions in the project-related phases, ranging from the early project definition till decommissioning and post-closure, throughout the whole life cycle of the project [26].

A protocol containing questions about the SLO components can have several functions, such as in the planning phase to query concerns and needs, existing expectations and fears a priori (***Figure 2***). Based on the results, adequate communication strategies can be derived. During further project development phases (exploration, drilling, construction, operation and decommissioning) the protocol can be used as a monitoring tool to make undesirable developments and dissatisfactions visible. In addition, it can be actively used as a participation tool by using the results as a basis for joint discussions and reflections with the local population and stakeholders, therefore enriching existing participation formats such as workshops or roundtables. Finally, it offers the function of evaluation and proof of impact, measuring to what extent the central SLO criteria have been achieved and a social license to operate exists. In this way, the SLO approach can be used continously over longer periods of time.

5. Conclusions

The presented study provides valuable insights into the nature of social acceptance on local level and its relationship with components of the Social License to Operate approach such as local identity, social impacts and trust. For future research, it would be important to conduct further studies using the presented standardised questionnaire in different case studies and at several measurement points in time, so that the comparisons enable a robust statement on the interrelationships of effects and variables used. Thus, the knowledge about the nature of SLO factors connected to geothermal projects can be deepened and enriched.

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Community Funding for Geothermal Energy

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Community funding is a tool to involve communities in geothermal projects in such a way that they can be involved in the decision making around the project and/or receive some of the benefits. There are different alternative finance instruments that give different options to involve investors from the community surrounding the project, thus realising community involvement, commitment, and funding for the project. These can be combined with risk mitigation instruments to limit the risk that community investors are exposed to. The characteristics of an individual project and the risk appetite and risk-absorbing capacity of community investors determine which combination of instruments is best suited. Because the outreach to, and involvement of, the community is very important for the acceptance, use and community support of geothermal projects, involving the community on the finance side of a project can be useful to make the successes and results of the project more accessible to the community.

Le financement communautaire est un outil pour impliquer les communautés dans les projets géothermiques de manière à ce qu'elles puissent être impliquées dans la prise de décision autour du projet et/ou recevoir certains des avantages. Il existe différents instruments de financement alternatifs qui offrent différentes options pour impliquer les investisseurs de la communauté entourant le projet, réalisant ainsi l'implication, l'engagement et le financement de la communauté pour le projet. Ceux-ci peuvent être combinés avec des instruments d'atténuation des risques pour limiter le risque auquel les investisseurs communautaires sont exposés. Les caractéristiques d'un projet individuel ainsi que l'appétit pour le risque et la capacité d'absorption des risques des investisseurs communautaires déterminent la combinaison d'instruments la mieux adaptée. Étant donné que la sensibilisation et l'implication de la communauté sont très importantes pour l'acceptation, l'utilisation et le soutien communautaire des projets géothermiques, impliquer la communauté du côté financier d'un projet peut être utile pour rendre les succès et les résultats du projet plus accessibles.

El financiamiento comunitario es una herramienta para involucrar a las comunidades en proyectos geotérmicos de tal manera que puedan participar en la toma de decisiones en torno al proyecto y/o recibir algunos de los beneficios. Existen diferentes instrumentos financieros alternativos que brindan diferentes opciones para involucrar a los inversores de la comunidad que rodea el proyecto, logrando así la participación, el compromiso y la financiación de la comunidad para el proyecto. Estos pueden combinarse con instrumentos de mitigación de riesgos para limitar el riesgo al que están expuestos los inversionistas comunitarios. Las características de un proyecto individual y el apetito por el riesgo y la capacidad de absorción de riesgos de los inversionistas comunitarios determinan qué combinación de instrumentos es la más adecuada. Debido a que el alcance y la participación de la comunidad son muy importantes para la aceptación, el uso y el apoyo comunitario de los proyectos geotérmicos, involucrar a la comunidad en el lado financiero de un proyecto puede ser útil para hacer que los éxitos y los resultados del proyecto sean más accesibles a la comunidad.

1. Introduction

One of the main objectives of the CROWDTHERMAL project is to empower the European public to directly participate in the development of geothermal projects with the help of alternative financing schemes. This article will present a summary of the financial schemes recommended for geothermal projects, taking in consideration the type of geothermal project, type of capital, financial risk and capital required for each project phase.

Community funding is the umbrella for alternative finance methods that are used to facilitate investment by the community directly into projects or companies. It is a way to financially involve the different stakeholders around a geothermal project. Community funding can bring a number of advantages to a geothermal project both by improving social involvement of the community and by contributing to the financial side of the project. Through community finance, members of the community choose which project or project category they want to invest in, and their repayment and return are (usually) connected to the success of the specific project or project category. The process of community funding can be realised via a platform, like a crowdfunding platform or a direct lending platform, or directly into bonds or shares issued by a project or company itself.

Community funding in general is focused more on impact and social context than just on financial reward. This makes it a suitable form of (co-)finance for geothermal projects where it is impor-

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tant to involve the community and other stakeholders.

Community funding comes in different shapes and sizes. It uses new finance schemes and old traditional ways. New fintech development can help to realise a community project at lower cost, because it can reduce the cost of the financing process or can realise funding where the bank would not provide loans It can also increase the outreach to all possible members, which makes the community project more effective. Geothermal projects could possibly benefit from using these new financing schemes.

The main advantages for a project developer to be gained by using community funding and these new financing schemes are:

- Outreach to a larger part of the community;
- More transparency for an involved community;
- Customer friendly process through use of digital models;
- Easy maintenance of the community funding project;
- Easier to comply with regulation thanks to a digital approach;
- Easier communication with the community group and individuals;
- Lower costs for the community funding project.

There are also advantages for the community members when community finance is used. This means these members can:

- Be more directly involved in the decision making around the project;
- Be actively involved in the realization of the project and its sustainability goals;
- Be better informed about the project;
- Receive some of the financial or other benefits (cleaner or cheaper energy) of the project.

Community finance is realised most easily by using alternative finance instruments. Alternative finance methods can be defined as any type of financial service managed outside the traditional regulated banking and capital market sectors. These services are driven by fintech and are part of a swiftly growing network of service providers that are linked to the digital ecosystem. [1]

2. Methodology

A number of best practices of using alternative finance in the sustainable energy field were studied to determine which types of alternative finance can be used to realise community funding in geothermal projects. Based on the lessons learned from these cases and the different phases of geothermal projects, a classification of financial risk of the different alternative finance instruments for community investors and a project developer was developed. Next, possible combinations with risk mitigation instruments were formed. Based on this information general guidelines for alternative finance in the different phases of a geothermal project have been developed.

Lessons learned from best practices were also used as a method to analyse community finance [2]. Important lessons learned were, e.g.: the need to focus on the impact of the project (sustainable energy) and not on the financial return, as this will increase the commitment of the community, or the advice to build a community first, as this can make the financing more successful. It is advised to start with a small, involved community and if that is successful, increase the target group for investment. The analysis of best practices revealed that there are several forms of community finance that can be promising for a geothermal project.

3. Alternative Finance and risk mitigation instruments

There are different alternative finance instruments that can be used to realise community funding. Examples are crowdfunding, direct lending, or social or green bonds. When choosing a certain finance instrument, it is important to look at the effects the use of a specific instrument has for the project developer and community investors. Some financial instruments are riskier for investors but also offer a higher possible return on investment. Other instruments may mean a stable return on investment and thereby less risk for investors but then often mean more risk for the project developer.

Alternative finance instruments can be combined with risk mitigation instruments to obtain the right mix of risk and return for all parties involved: the project owner, the involved community and other stakeholders, like local governments or other investors. The right mix of instruments to use depends on the risk appetite of the community and the project owner in a specific project and on the project phase in which the community funding will be used. It is important to realise that the specific circumstances of an individual project determine which combination of instruments fits best. It is not a one-size-fits-all situation.

A list of alternative finance instruments that can be used for community finance in geothermal projects is presented below. These instruments or ways to realise funding can use the mechanisms of crowdfunding or others. Crowdfunding can be defined as the practice of funding a project or venture by raising money from a large number of people who each contribute a relatively small amount, typically via the internet [3]. Alternatives to crowdfunding can be raising the money from a smaller group of individuals or a company, or from a government using these instruments.

Possible alternative financial instruments for geothermal projects are:

Donations
Where people donate money to a project with no return expected. Donations can be carried out with crowdfunding.

Reward-based funding
With reward-based funding the investors choose to invest in an individual project or company. The reward they receive is a non- monetary one. They can receive certain products, be invited to certain events or receive products at a discount. Reward-based funding can be carried out with crowdfunding.

Social impact bonds/Green Bonds
Social impact bonds and green bonds are debt instruments specifically designed to realise certain non-financial objectives. They look like a regular bond but are very different. A social impact bond is a “pay for success” financing instrument for projects that will create better social outcomes, where the payment to investors is flexible, based on the achieved results or savings. A green bond is a bond that is specifically earmarked to raise money for climate and environmental projects. It can be realised in the form of a social impact bond. Social impact bonds can be carried out crowdfunding.

Equity investments
With equity investments the investors also choose the project or company and invest, as with reward or output based funding, but as a reward they receive shares in the project or company. They will receive part

Table 1: Alternative finance instrument and their risks for community and project developers [5].

Risk ladder	*Risk profile*	*Community risk*	*Project developer risk*
Donations	*Risk absorbing*	*Very High*	*Very Low*
Reward based funding	*Risk absorbing*	*High*	*Low*
Social bonds, green bonds	*Risk absorbing*	*High*	*Low*
Equity investment	*Risk sharing*	*High*	*Low*
Revenue based funding	*Risk sharing*	*Medium-High*	*Medium-low*
Output based funding	*Risk sharing*	*Medium*	*Medium*
Leasing: Operational lease, ownership risk lies with owner/developer, users "rent" the asset	*Risk sharing*	*Medium*	*High*
Leasing: Financial lease, risks lie with user/community	*Debt*	*High*	*Low*
Direct lending Through crowdfunding, direct lending	*Debt*	*Low*	*High*
Match funding Through grants or donations	*Debt/risk sharing/ risk absorbing*	*Depends on character*	*Depends on character of funding*
Retained profits	*Reserves*	*Low*	*Low*

Table 2: Alternative finance instruments and risk mitigation.

Risk mitigation instruments	*Can be combined with*	*Risk reduction capacity*
Grant/subsidy	*All community finance methods*	*Medium*
Guarantee	*Social bonds, green bonds, leasing, loan products*	*High*
Match funding	*Loan products, leasing, maybe equity instruments*	*Medium*
Insurance	*All community finance methods*	*High*
Governmental lease	*Lease by the community/operational user*	*Medium*
Buy-back options (alternative form of operational lease)	*Equity, reward based, output based, revenue based*	*High*

of a project, but also share in the loss if a loss is incurred by the project. Equity investments can be done with crowdfunding.

Revenue-based funding
In revenue-based funding the investors only receive a reward based on the revenue realised. This reward can be financial or non-financial. Revenue based funding can be done through crowdfunding.

Output-based funding
In output-based funding the investors only receive a reward based on the quantity of output realised. This reward can be financial or non-financial. This can be done through crowdfunding.

Direct lending
Direct lending is a form of lending where a financial intermediary gives out bonds or other debt (fixed income) instruments to investors and uses the incoming funds to finance projects or companies, without going through a bank;

Leasing
Leasing is a process by which a firm can obtain the use of certain fixed assets for which it must pay a series of contractual, periodic, tax-deductible payments. It is a contract between the funder (lessor) and the end-user (lessee) for the acquisition and use of an asset and/or solution and (if included) any associated costs, such as maintenance in return for payment over an agreed period.

Match funding through grants or donations
Match funding is when a governmental organisation adds funding to funding generated by other investors in order to finance a project or company. The funding by other parties is often a requirement to receive match funding.

Retained profits
Retained profits are earnings kept from a project that can be used to finance the next phase of the project.

As mentioned, most of these instruments can be realised through crowdfunding. Crowdfunding means the funds are raised directly from the community. Crowdfunding and community funding overlap but are not the same thing. Crowdfunding usually raises also community funding, although institutional parties or (local) governments, who are not part of the crowd, can also invest. But community funding can also be realised in other ways, for example through social or green bonds and direct lending.

An interesting supporting instrument to increase the involvement of the community and other stakeholders is steward ownership. This is a form of ownership where all stakeholders involved, including employees can be owners of the company together. This means the company is not just driven by share value but more focused on realising the products and overall goal of the company. Steward ownership can be combined with all alternative finance instruments.

Another set of supporting instruments are risk mitigation instruments. Risk mitigation is a strategy to prepare for and lessen the effects of threats faced by a business [4]. In this context we focus on financial risk or threats. These can arise for the business, but also for other stakeholders like the community investors.

As community investors are usually investors with limited funds, it is difficult for them to reduce investment risk for themselves by diversifying their investments over different projects or companies. Geothermal projects can have high risks, especially during the first phases of

Table 3: General guidelines for alternative finance instruments for a geothermal project [10].

Project Phase	***Type of Capital***	***Financial Risk***	***Capital required***	***Suitable (Alternative) Finance Methods***
1. Project Definition	*Risk-absorbing, Risk-sharing*	*High*	*Low*	*Subsidies/grants/donations, crowdfunding (E/R), direct lending combined with governmental guarantee, governmental lease*
2. Exploration	*Risk-absorbing, Risk-sharing*	*High*	*Medium*	*Subsidies/grants/donations, crowdfunding (E/R), direct lending combined with governmental guarantee, governmental lease*
3A. Drilling First Well	*Risk-absorbing, Risk-sharing*	*High*	*High*	*Subsidies/grants, crowdfunding (E/R), governmental lease, direct lending combined with governmental guarantee, green bond, regular loan, regular bond, equity*
3B. Drilling – Resource Development	*Debt*	*High/ Medium*	*High*	*Crowdfunding ((E)/L/R), governmental lease, direct lending, green bond, regular loan, regular bond, equity*
4. Construction	*Debt*	*Low*	*High*	*Crowdfunding (L/R), direct lending, leasing*
5. Operation	*Debt*	*Low*	*Medium*	*Crowdfunding (L/R), direct lending, leasing*
6. Decommissioning & Post-Closure	*Reserves, Risk-absorbing (Government)*	*Medium*	*Low*	*Retained profits, governmental funds*

Note: E=equity, L=loan, R=reward-based

the project. To protect community investors from this risk, and the possible negative reputation of the project if things go wrong, risk mitigation can be very useful. Different risk mitigation instruments can be used to establish an appropriate risk-return profile for all parties involved. Some examples are guarantee instruments, fiscal instruments or smart contracts.

To create insight into the different risk consequences for parties involved, Table 1 gives a general indication of the risks involved for different parties when investing in geothermal projects using different alternative finance instruments.

When looking at the adjustment of the risk-return profile by using risk mitigation instruments, not all combinations will be successful [5]. ***Table 2*** gives an overview of which risk mitigation instrument can be of added value to which alternative finance instruments.

4. Matching alternative finance instruments to a geothermal project

The possible alternative finance instruments and their combination with risk mitigation instruments have now been explained. The next step is to look at if a developer or community wants to use alternative finance instruments and which alternative finance instrument might suit a specific geothermal project.

Guidelines have been developed containing all the relevant steps when considering the involvement of a community in geothermal projects, both through social involvement tools and community funding [6]. When choosing community funding there are a number of follow-up questions to answer to choose the most suitable alternative finance instrument. To assist with the answering of these questions, a conceptual framework has been developed [5].

In this framework the following tasks have to be completed:

1. Define the involvement goals of the project [7]
   Why does the project developer want to involve the community, what does he/she want to achieve by involving it?
2. Define and select the relevant community [8]
   Which community fits this goal, who are they?
3. Define the community's (risk) profile
   What is the social and financial situation of this community?
4. Define the appropriate risk level for the community, and also for the project developer
   What risk can the community absorb, and how does this risk potentially influence the goals?
5. Define the finance and risk mitigation options
   Which combinations of financial instruments and risk mitigation instruments fit the goals and community of a specific project (developer)?

We must bear in mind that the characteristics of each individual project are different, which means there is not one always applicable best solution. However, it is possible to give a general indication of which instrument suits which category of projects.

There are four main factors specific to a project that determine the suitability of instruments:

- The first factor is the project phase a project is in when the financing is required.
- The second factor is the type of capital which would suit this project phase. The type of capital can be:
- risk absorbing (when the capital takes risk away from the project owner or other investors);
  - risk sharing (when the capital shares in the risk with the project owner or other investors);
  - debt (which always has to be repaid thus possibly increasing the risk for the project owner or other investors), or
  - retained profits (which are generated by the project itself).
- The third factor is the financial risk. This is mainly determined by the project phase the project is in, but can also be influenced by other characteristics of a certain project [9].
- The fourth factor is the amount of capital required. Typically, the amount of capital in, for example the definition phase is low, while capital required in the drilling phase is much

more. Again, this can vary from project to project.

These factors together can give a general indication which alternative finance methods could be suitable for a certain project, as indicated in ***Table 3***. Using all this information a suitable community finance approach for a geothermal project can be developed (keeping in mind that project-specific circumstances will determine the actual possibilities).

5. Conclusions

Alternative finance and especially community funding can successfully be used for different geothermal projects and technology types as well as various investment sizes, and these funding sources can increase the involvement of the community in geothermal projects. Successful community funding needs to match the actual technical and financial characteristics of an individual geothermal project with the community investors' risk appetite and motivation for involvement. The community finance method most suited for a certain project depends on a number of factors, which means case-by-case evaluation is needed as to which method should be chosen. Each project phase requires a different financial instrument to match the risk profile, the amount of capital needed, and the kind of capital needed.

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The H2020 project REFLECT - Redefining fluid properties at extreme conditions to optimise future geothermal energy extraction

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The efficiency and feasibility of geothermal utilisation depends strongly on the characteristics and behaviour of the fluids that transfer heat between the geosphere and the engineered components of a power plant. Chemical and physical processes such as precipitation, corrosion, or degassing are induced by pressure and temperature changes, with potentially serious consequences for power plant operation and project economics. The EU Horizon 2020-funded project REFLECT aims to avoid such problems by collecting high-quality chemical, physical, and microbiological data at extreme salinities, pressures or temperatures and improving the understanding of kinetic processes through laboratory experiments. These data are presented in a European geothermal fluid atlas and implemented in predictive models in order to provide recommendations on how to best operate geothermal systems for a sustainable future.

L'efficacité et la faisabilité de l'utilisation de la géothermie dépendent fortement des caractéristiques et du comportement des fluides qui transfèrent la chaleur entre la géosphère et les composants techniques d'une centrale électrique. Les processus chimiques et physiques tels que les précipitations, la corrosion ou le dégazage sont induits par les changements de pression et de température, avec des conséquences potentiellement graves pour le fonctionnement de la centrale électrique et l'économie du projet. Le projet REFLECT, financé par l'UE Horizon 2020, vise à éviter de tels problèmes en collectant des données chimiques, physiques et microbiologiques de haute qualité à des salinités, pressions ou températures extrêmes et en améliorant la compréhension des processus cinétiques grâce à des expériences en laboratoire. Ces données sont présentées dans un atlas européen des fluides géothermiques et mises en œuvre dans des modèles prédictifs afin de fournir des recommandations sur la meilleure façon d'exploiter les systèmes géothermiques pour un avenir durable.

La eficiencia y viabilidad de la utilización geotérmica dependen en gran medida de las características y el comportamiento de los fluidos que transfieren calor entre la geosfera y los componentes de ingeniería de una planta de energía. Los cambios de presión y temperatura inducen procesos químicos y físicos como la precipitación, la corrosión o la desgasificación, con consecuencias potencialmente graves para el funcionamiento de la planta de energía y la economía del proyecto. El proyecto REFLECT, financiado por la UE Horizonte 2020, tiene como objetivo evitar tales problemas mediante la recopilación de datos químicos, físicos y microbiológicos de alta calidad a salinidades, presiones o temperaturas extremas y mejorando la comprensión de los procesos cinéticos a través de experimentos de laboratorio. Estos datos se presentan en un atlas de fluidos geotérmicos europeo y se implementan en modelos predictivos para brindar recomendaciones sobre cómo operar mejor los sistemas geotérmicos para un futuro sostenible.

1. Introduction

The one problem plaguing almost all deep geothermal operations in the world is the in-situ chemistry of the geothermal fluids. In order to maximise the technical feasibility, operational efficiency and economic returns of geothermal power plants, it is vital that these systems work well for long periods without requiring significant maintenance. Key to this is preventing deleterious physical and chemical reactions such as degassing and mineral precipitation (see ***Figure 1***). Currently, accurate prediction of those reactions is difficult, due to poorly defined fluid properties, largely as a consequence of the difficulty in determining these properties at in-situ geothermal conditions (i.e., extremely hot or extremely saline fluids). The European project REFLECT - Redefining fluid properties at extreme conditions to optimise future geothermal energy extraction, funded by the European Commission in the research and innovation programme Horizon 2020, addresses these challenges and extends the presently limited experimental data on the thermodynamic and thermophysical properties of high temperature brines for various salt contents. Using the knowledge on fluid properties generated in REFLECT, the range of application for geothermal energy conversion can be significantly expanded to

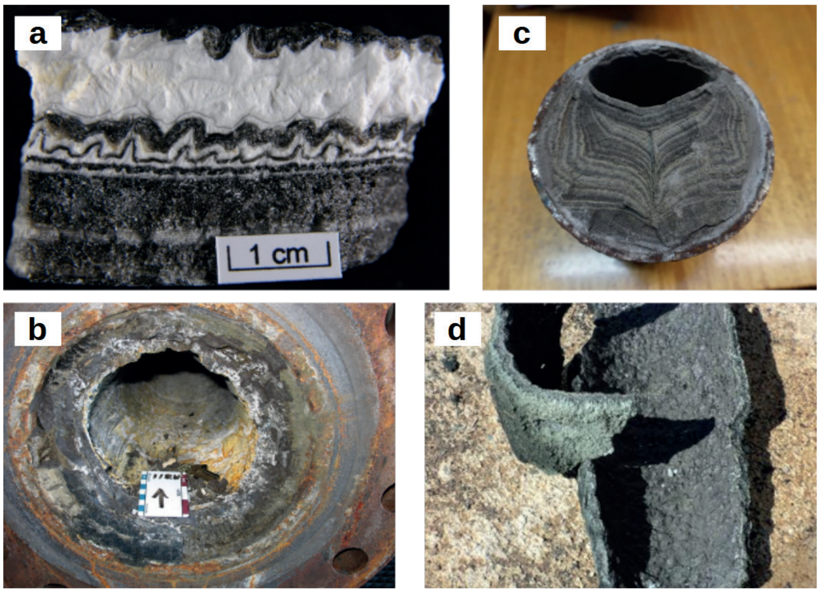

Figure 1: Examples of scaling, one of the most common problems in geothermal operations. (a) silica scale, Reykjanes, Iceland; (b) sulfide scale, Iceland (both © V. Hardardottir); (c) calcite scale, Hungary (© Z. Istfan); (d) Fe, Mg scale, Tuzla, Turkey (© A. Baba).

hotter and more saline conditions.

In the project, 14 partners from geothermal research, industry, and geoscience associations work together to redefine fluid properties for future geothermal energy extraction. They combine expertise from geochemistry, material science, geothermal, geology, microbiology and engineering in order to narrow the knowledge gap in this field, leading to more reliable predictions of geothermal performance.

By addressing the main problems of geothermal operations (scaling, degassing, and corrosion), REFLECT results will offer solutions to avoid those problems. These solutions decrease operation and maintenance costs, minimise downtimes, and increase the overall reliability and efficiency of operations. REFLECT will, therefore, have a significant influence on the development of geothermal systems and on the overall electricity and heat supply generated from renewable energy sources. The project's main impact will thus be improved EU energy security: by encouraging an increase of the share of geothermal energy within the European energy market, REFLECT can help to reduce the consumption of fossil fuels, reduce dependence on non-EU suppliers and approach the aims of the Paris agreement.

The key objectives of the REFLECT project can be summarised as to:

1. Extend databases (solubility, activity, reaction kinetics) to higher temperatures and higher salinities through lab experiments and modelling approaches;
2. Determine the extent and location of the degasification front of geothermal fluids during production (field, lab, and modelling approaches);
3. Determine types of organic matter and microorganisms in various geothermal fluids and their effect on scaling and biofilm formation via laboratory studies;
4. Determine heat capacity, density, electrical and thermal conductivity, sonic velocity, and viscosity at various pressures, temperatures and salinities (p, T, X) through lab experiments and modelling approaches;
5. Develop a down-hole sampling technique suitable for collecting fluid at a chosen depth in hot and super-hot systems;
6. Verify and implement the improved dataset by application in reactive transport modelling;
7. Set up a Geothermal Fluid Atlas that collates information on geothermal fluid properties across Europe together with their geological setting.

In the following, we will briefly describe how each of the objectives is addressed in the project and which methods are applied.

2. Objectives and Methods

2.1. Extend databases (solubility, activity, reaction kinetics) to higher temperatures and higher salinities

Relevant fluid properties have been measured on samples from 13 geothermal sites across Europe (*Figure 2*). The sampling campaign has been severely impacted by border closures and lack

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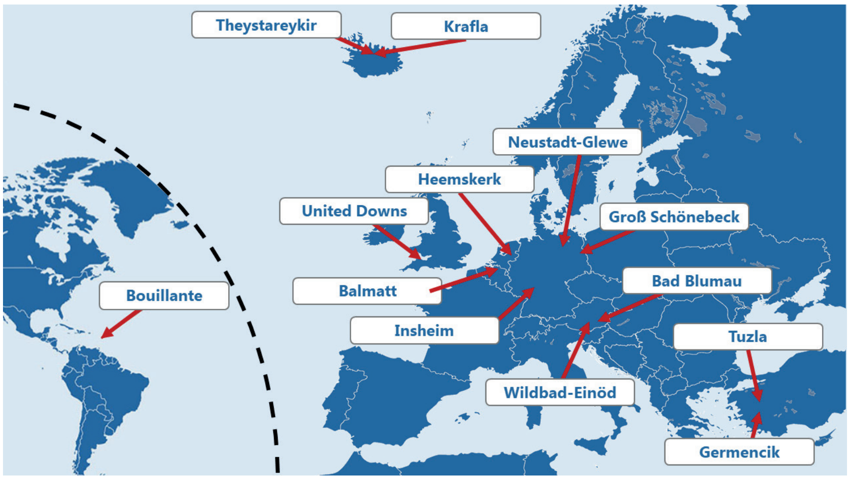


Figure 2: Geothermal sites from which samples were obtained for the analysis of organic and inorganic chemistry, and partly for microbiological analysis.

of access to geothermal sites due to the Covid-19 pandemic. Nonetheless, fluid samples were acquired from Insheim (DE), Bad Blumau (AT), Heemskerk (NL), Neustadt-Glewe (DE), Groß Schönebeck (DE), Wildbad-Einöd (AT), United Downs (UK) and additionally from high enthalpy sites Bouillante (FR), Krafla (IS), Theistareykir (IS), Tuzla (TR), and Germencik (TR). Additional fluid samples were obtained from Balmatt (BE) through SKC-CEN (member of the project's advisory board). Sampling protocols were shared among the participants to avoid contamination and ensure equal treatment of samples before transport and subsequent analysis in the labs. Partners of the consortium characterised the sample properties by measuring the main and minor cations and anions (HI, ÍSOR), bacteria and spores (UNINE), organic components (GFZ), dissolved gases (HI), silica (BGS/UKRI, IZTECH, LVK), NORM (GFZ), and selected isotopes (HI). Sample collection was usually above ground at the wellhead, where the average fluid was sampled. At some sites, several samples were taken in different locations in the circulation system (at the production well, shortly before or after the heat exchanger, and before injection) in order to analyse changes in chemistry and microbiology due to the changing conditions (i.e. reduced temperature and pressure).

The consortium of REFLECT operates and has expertise in instruments and equipment that resist the corrosive nature of brines and that allow the characterisation of a range of fluid properties. This also enables the collection of thermodynamic and kinetic data by enabling novel experiments at up to 400 °C and 400 bar.

Solubility and speciation of silica and Si-metal species in 'superhot' fluid systems have been detected *in situ* via spectrometry, and *ex situ* via more traditional fluid sampling techniques. For example, Kummerow et al. [1] use electrical conductivity measurements to monitor the progress of calcite dissolution or precipitation from H_2O-NaCl-CO_2 solutions and to define equilibrium conditions.

2.2. Determine the extent and location of the degasification front of geothermal fluids during production

Decreasing pressures towards the production well can lead to the exsolution of gas from geothermal waters in the near-well region. This can cause problems like corrosion of the facilities or reduced water production. The degassing of CO_2 and N_2 saturated water has been studied using a visual cell and a high-speed camera at elevated pressures (up to 200 bar) and temperatures (up to 150 °C).

Colleagues from TU Delft also used a PEEK (polyether ether ketone) core holder in CT-assisted coreflood experiments, i.e. gas-brine flow experiments in rock cores (*Figure 3*). The experimental setup is designed for visualising the emergence of free gas bubbles during CO_2-brine coreflood experiments and determining to what extent the flow is affected by these bubbles. A model for CO_2 solubility in brine was created to assess whether the start of degassing (i.e. the bubble point) can be predicted accurately by comparing its results to that of the experiments.

2.3 Determine types of organic matter and microorganisms in geothermal fluids and their effect on scaling and biofilm formation

Microorganisms are present in most ecosystems on Earth, and despite the extreme environmental conditions in geothermal fluids, these systems are also home to microbial life. Inside power plant systems, microorganisms can be involved in microbially induced corrosion (MIC), form biofilms or induce mineral precipitation. One striking example of the impact of microorganisms on power plants is the induced precipitation of silica by bacteria, which strongly decreases the efficacy of a

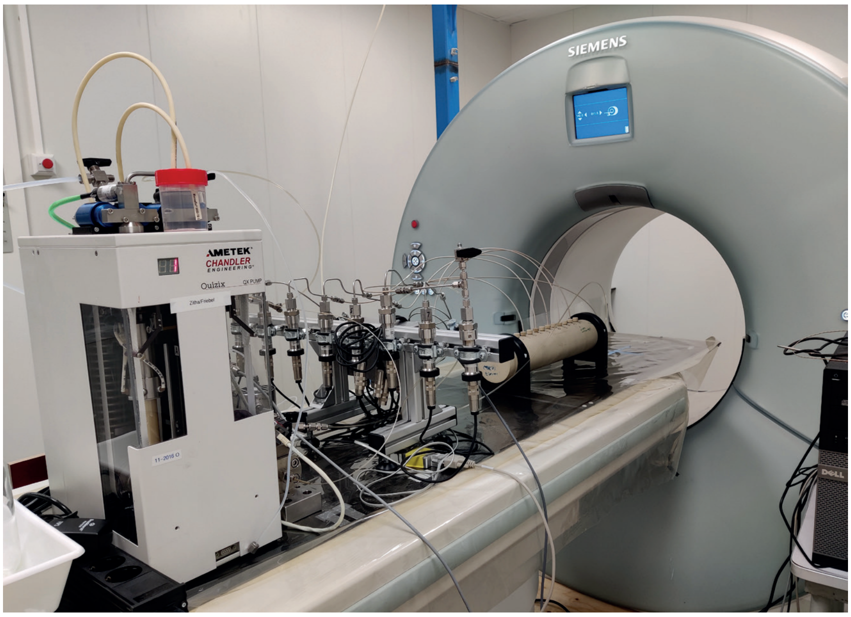


Figure 3: The core flooding setup using the PEEK core holder in the CT scanner. The setup at TU Delft is used to assess the extent to which free gas is limiting water flow inside rocks.

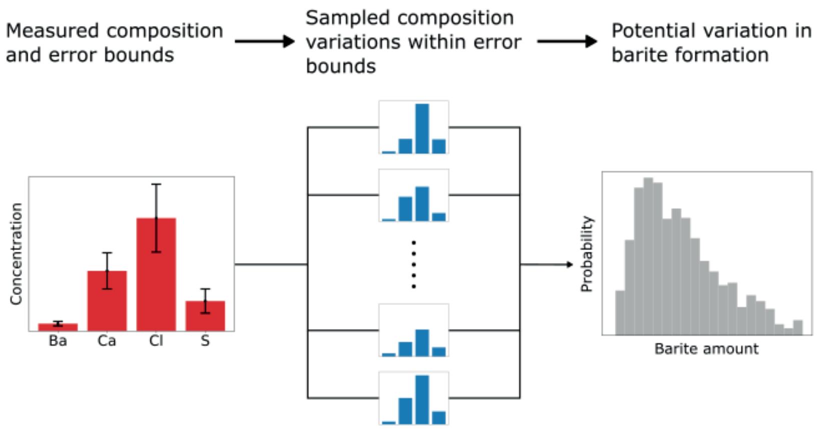

Measured composition and error bounds
Sampled composition variations within error bounds
Potential variation in barite formation
Concentration
Ba
Ca
Cl
S
Probability
Barite amount

Figure 4: Graphical depiction of the uncertainty quantification approach (from [11]).

power plant [2].

However, other than in specific cases [2,3,4], knowledge of the diversity and prevalence of microbial life in deep geothermal reservoirs is still scarce. In order to fill in this knowledge gap, microbial life at extreme conditions has been studied by researchers of the University of Neuchatel by sampling 8 geothermal sites with a temperature range of 47–345 °C. During sampling large volumes of water (~40 l per sample) were filtered in order to concentrate the biomass in the filter product. From the concentrated biomass, DNA was isolated and used for sequencing, and microbes have been cultivated under laboratory conditions. This approach enables assessment of the diversity of microbial species present in different geothermal settings.

The origin, composition, and fate of dissolved organic matter (DOM) within deep geothermal reservoirs is relatively unknown. Natural DOM as well as artificial DOM (e.g. from chemical scaling inhibitors), might serve as nutrients for microorganisms or affect chemical properties of the fluids by complexation. The organic compounds in natural geothermal fluids were investigated by GFZ at 10 sampling sites. The thermal stability of organic components has been monitored by Fourier Transform IR spectroscopy (instrument with integrated high p-, T cell) and liquid chromatography organic carbon detection (LC-OCD).

TNO investigated the effect of organic complexes and colloids on flow properties and precipitation. The effect of several common carboxylic acids on the formation of homogeneous calcium carbonate scale was investigated and a novel method (dynamic light scattering) has been developed.

2.4 Determine heat capacity, density, electrical and thermal conductivity, sonic velocity, and viscosity at various pressures, temperatures and salinities

Thermophysical data (density, viscosity, thermal- and electrical conductivity, heat capacity, sonic velocity) are required for reliable geothermal site assessment and development (e.g. for exploration, reservoir engineering, well and pump design and power plant layout). While the database for binary solutions with water and one salt (usually NaCl) is good, information for more complex and high salinity fluids (e.g. ternary solutions) is scarce.

GFZ researchers performed laboratory scale measurements of fluid density and heat capacity on synthetic NaCl and $CaCl_2$ aqueous mixtures. Different cation ratios were explored for total molalities up to 6 $mol \cdot kg^{-1}$. Pressure and temperature ranged between 0.1 and 40 MPa, and 20 and 80 °C, respectively. An Anton Paar DMA4500M was used for density measurements at ambient pressure, whereas the DMA HP external density measuring cell measured density up to 700 bar and 200 °C. Approximately 700 new experimental measurement and data points were generated [5].

In a second experimental approach, electrical conductivities of carbonate solutions at different concentrations were measured at up to 450 °C to determine limiting conductivities and association constants [1]. In the first set of experiments the electrical conductivity of multi-component brines, representing the composition of natural geothermal fluids and consisting of variable mole fractions of NaCl, $CaCl_2$, KCl, $NaHCO_3$, Na_2SO_4, K_2SO_4 was measured in a high-temperature flow-through cell up to 450 °C. In the second set of experiments, binary carbonate solutions at various concentrations were measured in the flow-through cell to determine the limiting electrical conductivity up to 450 °C and to extract information on the molar association constants for the ions in solution.

Finally, Lassin and André [6] developed a new thermodynamic model for the H-Li-Na-K-Ca-Mg-Cl-H_2O chemical system, from dilute solutions up to salt solubility, and for temperatures up to 250 °C. This model relies on the Helgeson-Kirkham-Flowers (HKF) and the Pitzer equations, and considers the partial dissociation of the $CaCl_2$ electrolyte. It has been implemented in the PhreeSCALE geochemical calculation software [7] to compute properties such as heat capacity, enthalpy, and density of chloride-bearing multi-electrolyte solutions in conditions relevant for the production of geothermal energy.

2.5 Develop a down-hole sampling technique suitable for collecting fluid at a chosen depth in hot and super-hot systems

Sample collection usually occurs at the wellhead, where the average fluid is sampled (i.e. a mixture of fluids from any inflows feeding the productive section(s) of the well). However, when multiple feed zones of deep wells blend, the local fluid conditions can cause corrosion and/or scaling in the perforated liner and production casing. Consequently, the lack of knowledge about fluid properties of distinct aquifers leads to long-term and high-cost geothermal utilisation problems. Downhole sampling of the fluid at depth provides information on the fluid composition that enables optimal design of downhole and surface installations to prevent operational problems.

In course of the project, a downhole sampler was designed that is capable of collecting fluids at higher temperatures and pressures than the existing ones (together with an appropriate extraction line). High-temperature sampling scenarios in liquid phase, two-phase, saturated steam and superheated/supercritical conditions were defined. The fluid sampler developed [8] will be able to sample high-temperature geothermal wells of 200–300 °C, but the more ambitious aim is to adapt the design for even higher temperatures (up to 400 °C) and supercritical pressures.

A first proof-of-principle sampling test will be performed by the REFLECT team at a low-temperature well in early 2023.

2.6 Verification and implementation of the improved dataset by application in reactive transport modelling

Two modelling tools were further developed to predict scaling behaviour and flow properties of geothermal fluids during energy generation.

First, the numerical code porousMedia4Foam was developed in order to predict scaling risks on the geothermal fluid's path towards the surface, when its chemical equilibrium is disturbed. It is an open-source, multi-scale and multiphase package, where OpenFOAM® is coupled with the PHREEQC code (a geochemical model which is used to simulate the precipitation amount and kinetics of different geothermal minerals, see [9]) to investigate hydro-geochemical interactions. The flow, transport of chemical species, evolution of porous media properties, and temperature are handled by solving equations implemented in OpenFOAM®, whereas the chemistry is exclusively handled by PHREEQC.

Second, a workflow was developed to enable a better estimation of the location and amount of precipitated minerals in different locations of a geothermal system, focusing on processes in the surface installations [10]. A multiphase flow solver was coupled to thermodynamics libraries and PHREEQC. A detailed roughness model was developed to simulate the impact of mineral deposition on the fluid flow. In addition, an uncertainty quantification workflow was combined with the modelling framework to estimate the uncertainty bounds of the scaling and precipitation resulting from uncertainties in the fluid composition characterisation and operational settings (*Figure 4*).

2.7 Set up a Geothermal Fluid Atlas that collates information on geothermal fluid properties across Europe

The last objective of REFLECT was to set up the European Geothermal Fluid Atlas (EFA, ***https://reflect.uni-miskolc.hu/efa***) to provide a comprehensive data collection of properties of geothermal fluids used for electricity production (T>100 °C) along with information of the well, reservoir, and host rock. The first step was to create an exhaustive template for data collection. Existing fluid data from all over Europe was collated in cooperation with 20 EU countries (national geological associations that are members of the European Federation of Geologists) to generate a consistent and accessible database [12]. Together with properties of natural fluids analysed in REFLECT [13] these data form the basis for the European atlas on fluid properties, which is set up by the University of Miskolc. Furthermore, an approach will be developed to transfer the available fluid data into risk estimations for different operational issues by incorporating the data in numerical modelling.

3. Results and Discussion

Due to the complex nature of the project and the multitude of results, only a selection of results is described here. The reader is kindly asked to refer to project deliverables and further publications to find details on the results obtained. As for the methodology, the following section is structured in subsections that are aligned with the seven key project objectives.

3.1. Extend databases (solubility, activity, reaction kinetics) to higher temperatures and higher salinities

Data of the samples collected from 13 geothermal sites were published in two Deliverables: Iannotta and Hehn [14] for the eight high-saline geothermal sites and Baba et al. [15] for the five high-temperature sites. Analysis of major and minor cations and anions was limited to the elements that are usually abundant in geothermal systems. In the future, however, it would be desirable to extend the analysis to elements that are considered critical raw materials. Detailed analysis of the geochemistry of fluids, rock samples, and precipitates was performed at the two Turkish sites, Germencik [16] and Tuzla [17]. Knowledge from this analysis was also included in the investigation on Antimony (Sb)-rich geothermal deposits and their solubility in presence of different antiscalants with various functional groups. Karaburun et al. [18] found that macromolecules containing sulfonic acid groups and poly (vinyl sulfonic acid) derivatives could potentially act as antiscalants for the formation of antimony sulphide.

Solubility experiments for calcite solutions [1] showed that the solubility of calcite in all tested solvents decreases exponentially with increasing temperature at constant pressure, while the solubility increases with increasing pCO_2 at isothermal conditions.

Further studies on the kinetics, solubility, and Pitzer activities of silica and metal-silica precipitates are ongoing. Results from these experiments will be published in deliverable D1.4 and D2.3. Still, these studies are just a first step towards a better understanding of precipitation. In the future, it would be desirable to repeat the experiments with more complex fluids (i.e. containing multiple anions/cations) that mimic the chemistry of natural fluids.

3.2 Determine the extent and location of the degasification front of geothermal fluids during production

High speed imaging of degassing kinetics of CO_2-water mixtures revealed that when CO_2 is in a gaseous state, the formation of the first free gas bubbles is in reasonable agreement with the van ‘t Hoff equation, which dictates the solubility of gases at elevated temperatures. However, this is not the case for experiments at higher initial pressure (>73.8 bar), which start out with CO_2 in a supercritical state. Here the bubble point pressure is consistently lower than the expected bubble point based on the Van ‘t Hoff equation. Further information can be found in separate articles on these experiments [19,20,21].

The coreflood experiments showed that the formation of free gas can reduce the water relative permeability by up to 50% in a high permeability Bentheimer sandstone and up to 90% in a low permeability Berea sandstone (an Upper Devonian sandstone

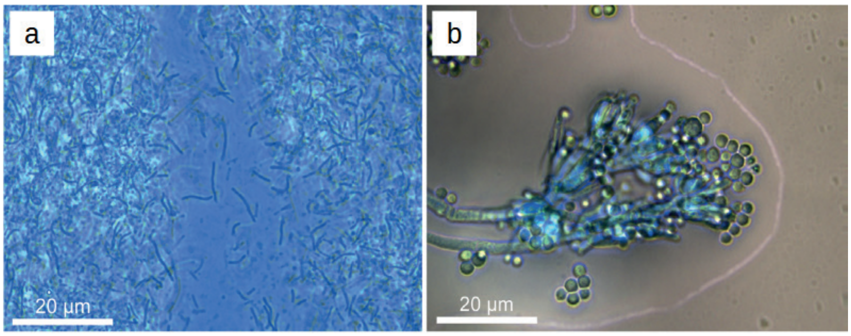


Figure 5: Microscopical (optical microscopy) images of two microbial strains isolated from geothermal power plants. (a) Bacteria (b) Fungus.

formation from north-east USA) [21]. The bubble point does not vary between the two different rocks. The CT-assisted corefloods show increasing gas saturation inside the core as the pressure is reduced. Gravity override due to a difference in density between the gas and liquid phase was also observed in these experiments.

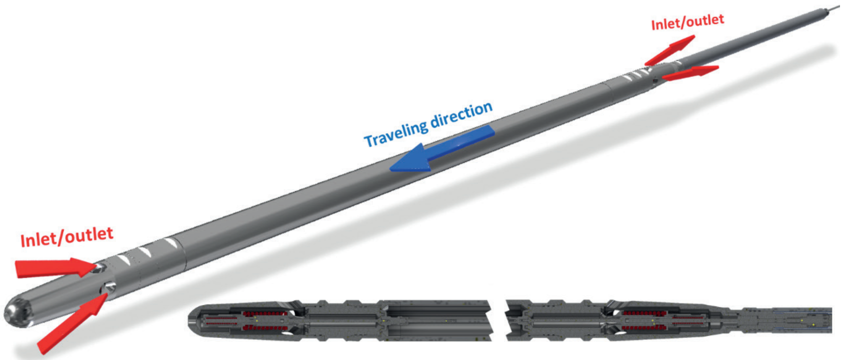


Figure 6: REFLECT downhole sampler developed to sample various phases (liquid, two-phase, steam) at low to high temperature/high pressure superheated/supercritical conditions in geothermal wells.

3.3 Determine types of organic matter and microorganisms in geothermal fluids and their effect on scaling and biofilm formation

The review of Leins et al. [22] and the connected data publication [23] reviewed data on organic compounds in geothermal fluids of 143 fluid samples from 22 geothermal sites. The study observed lower dissolved organic carbon (DOC) concentrations in the lower temperature ranges (30–80 °C), which might be explained by microbial degradation of DOM in this temperature range. Thermal degradation of DOM accounts for the decreasing DOC concentrations in the temperature range of 80–200 °C. Higher salinity of the fluids might limit microbial activity, leading to higher possible DOM content in more saline brines. Hydraulic connections to organic-rich sediments or oil-bearing strata within the reservoir can be detected by investigating the DOM content and composition of the geothermal fluids.

The review of Bregnard et al. [24] investigated the information on microbiological diversity in geothermal fluids. The researchers also studied the microbiological diversity at six of the sampling sites investigated in REFLECT. In the analysis they found different bacterial signatures for each power stations. They were able to isolate specific bacteria, but also fungi, from geothermal systems (see *Figure 5*). The temperature does not seem to be the dominating factor when it comes to diversity in general, since many microbes can form dormant, resistant spores that can survive unfavourable conditions and be reactivated as soon as the conditions are favourable again (e.g. when temperatures drop in the heat exchanger).

The effect of several common carboxylic acids on the formation of homogeneous calcium carbonate scale was investigated using dynamic light scattering [25], which has proven to be a new method to study important aspects of homogeneous nucleation like induction time and relative amounts of precipitate formed [26]. All carboxylic acids tested in this research had an inhibiting effect on the precipitation of calcium carbonate. Both the induction time and amount of precipitation were influenced by the carboxylic acids: an increase in concentration of acid groups results in an increase in induction time and a reduction in the total amount of scaling/precipitation.

3.4 Determine heat capacity, density, electrical and thermal conductivity, sonic velocity and viscosity at various pressures, temperatures and salinities

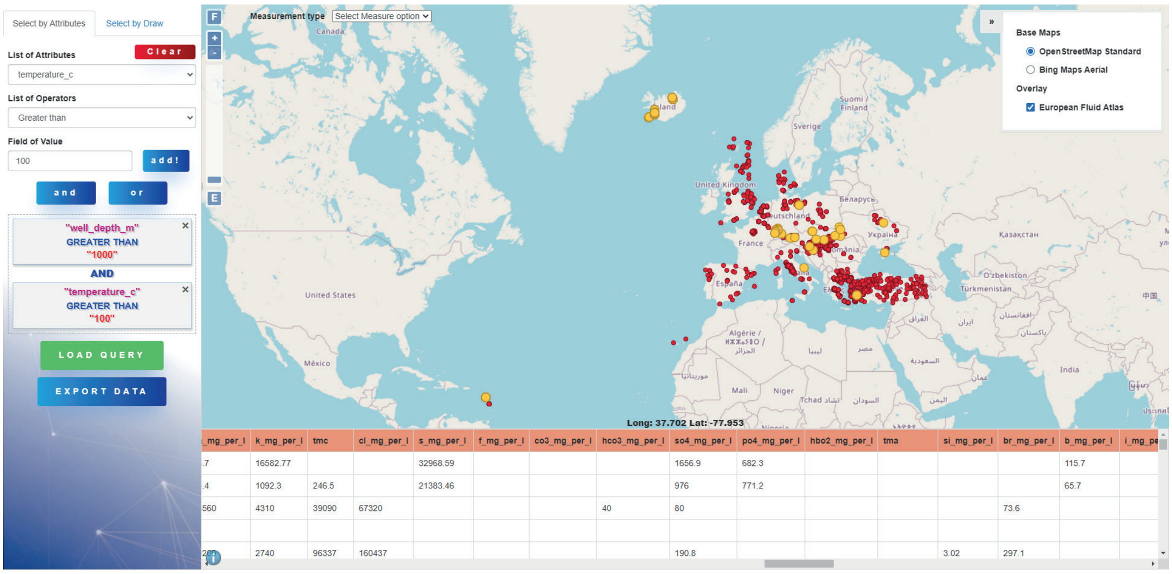
The 700 measured data points for fluid density and heat capacity of synthetic NaCl and $CaCl_2$ aqueous mixtures [5] were provided to the partners at BRGM for modelling. In a blind test, the model of [6] for the NaCl-$CaCl_2$-H_2O system was used to calculate density and heat capacities of the solutions experimentally investigated. The model produced a very good match for density and heat capacity in NaCl solutions, with errors lower than 2% (except when chloride concentration exceeds 9 $mol \cdot kg^{-1}$). For calcium chloride system, a good match is observed up to 3 $mol \cdot kg^{-1}$. The model will hence be able to produce valuable predictions for various salt concentrations.

Experimentally, limiting conductivities of the binary aqueous $NaHCO_3$ system were determined in the temperature range 24–450 °C from measured equivalence conductivities of solutions of four different concentrations (0.1 M, 0.05 M, 0.01 M, 0.001 M). The results for sodium-bicarbonate show that up to 200 °C limiting conductivities increase linearly with temperature, but decrease again for higher temperatures. The new data allow the calculation of electrical conductivities of aqueous $NaHCO_3$ solutions at any concentration. This may also allow us to develop numerical models that better describe the electrical conductivity of complex salt solutions for given temperature and pressure parameters than the established equations derived from measurements on binary solutions.

3.5 Develop a down-hole sampling technique suitable for collecting fluid at a chosen depth in hot and super-hot systems

For the downhole sampler developed by ÍSOR, a flow-through design (*Figure 6*) has been selected as the most reliable principle. A special emphasis was put on the selection of corrosion resistant and leak-tight materials and parts suitable for construction of the downhole sampler. Since the sealing of the sampler will be one of the most crucial mechanisms, different materials for seals have been chosen, which can be adapted to the temperature/pressure conditions aimed for during sampling (e.g. metal-to-metal seals for superheated, high-pressure wells, and high-temperature polymer seals for wells up to 300 °C). Samples will be collected at depth with sampling volume up to 1000 ml. The sampler's delayed clocking mechanism will close the sampler at sampling depth. The sample is then taken to the surface, allowing for isochoric temperature and pressure decline.

Another challenge that was addressed by project partner Hydroisotop is the transfer of gas-rich liquids or steam-water mixtures from the downhole sampling tool to adequate sampling containers that can be safely transported to a laboratory for further analysis. In order to transfer samples from the downhole sampling tool to sample cells without contamination, a structure is required that allows for vertical positioning of the sampling tool and all sample cells. Cooling of the sampling tool upon retrieval from the well results in pressure loss and can lead to degassing. To avoid or reverse degassing, the upper part of the sampling tool needs to be pressurised.



Measurement type: Select Measure option

List of Attributes: temperature_c

List of Operators: Greater than

Field of Value: 100

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AND

"temperature_c" GREATER THAN "100"

● OpenStreetMap Standard

○ Bing Maps Aerial

☑ European Fluid Atlas

Long: 37.702 Lat: -77.953

_mg_per_l	k_mg_per_l	tmc	cl_mg_per_l	s_mg_per_l	f_mg_per_l	co3_mg_per_l	hco3_mg_per_l	so4_mg_per_l	po4_mg_per_l	hbo2_mg_per_l	tma	si_mg_per_l	br_mg_per_l	b_mg_per_l	i_mg_pe
.7	16582.77			32968.59				1656.9	682.3					115.7	
.4	1092.3	246.5		21383.46				976	771.2					65.7	
560	4310	39090	67320				40	80					73.6		
2[illegible]	2740	96337	160437					190.8				3.02	297.1		

Figure 7: Screenshot of the European Geothermal Fluid Atlas with location of the 2,400 wells where already existing well, fluid, rock and reservoir data were collected. The example shows the query for wells with depth > 1,000 m and temperature > 100°C, resulting in the locations on the map marked with yellow dots.

First results from an initial test of the downhole sampler and the extractions system at a low-temperature well are expected towards the end of the REFLECT project.

3.6 Verification and implementation of the improved dataset by application in reactive transport modelling

Soulaine et al. [27] described the developed coupled hydro-thermal-chemical software porousMedia4Foam and made the source code as well as some tutorials available on GitHub: ***https://github.com/csoulain/porousMedia4Foam*** [28]. A User's Guide to the software is available as REFLECT Deliverable 4.1 [29]. The software porousMedia4Foam has been extensively validated for single phase flows at different scales, i.e. at the pore-scale and continuum-scale, for which reference solutions exist. For example, Soulaine et al. [27] demonstrated the ability to simulate dissolution and precipitation processes in fractured porous media at the pore-scale using the hybrid-scale approach. In their study, the reactive medium consisted of celestite grains that reacted with a barium chloride solution injected into the system, leading to the dissolution of celestite and the growth of barite. The model can also be used to simulate the reactivity of the fluid in the geothermal well, especially the potential re-circulation of fluid developing at the corners of the expanding well cross-sections that could modify chemical concentrations in the fluid and potentially impact the saturation indices of precipitating minerals [30].

The modelling and uncertainty quantification workflow was demonstrated on a barite precipitation case study in a heat exchanger [11]. Initially, the impact of geochemical uncertainties (in the fluid composition) on the mineral precipitation was assessed. Afterwards, the coupled fluid flow and precipitation model with the developed roughness model was tested. Finally, the coupled uncertainty quantification workflow with the coupled model was simulated to assess the impact of fluid composition uncertainties on mineral deposition. As an outcome of the simulation, the impact of uncertainties in the mineral deposition on reduction in the production rate and heat transfer (within the heat exchanger) was calculated. The sample code to perform uncertainty quantification with geochemical modelling using PHREEQC and instructions on using the code are available on Github: ***https://github.com/poortjp/REFLECT_D4-3_example***. Using the presented workflows, it is possible to predict the occurrence and severity of various scaling types within a geothermal system, its effects on the decrease in flow rate over time, and the expected potential variation of these results based on the uncertainty in brine composition.

3.7 Set up a Geothermal Fluid Atlas that collates information on geothermal fluid properties across Europe

The European Geothermal Fluid Atlas collates information from pre-existing geothermal fluid data and data analysed during the project (see Section 3.1). For the atlas, a free and open-source cross-platform is used in which the geographic information system provides the environment to view and analyse geospatial data. The entire dataset is available for query and download through the website ***https://www.reflect-h2020.eu/efa***. The interface includes query and filtering tools to explore the database with map-based visualisation (*Figure 7*). Since many fluid data were submitted with additional comments or complementary information, an additional data sheet or report containing this additional information is available for each fluid sample.

With the Fluid Atlas, we aim to provide a tool to rapidly access known geothermal fluid properties all over Europe, and proxy correlation with host rocks and reservoir formations. The compositional maps are used for estimations of risk for the different operational issues, in combination with numerical modelling. The Fluid Atlas can be later integrated into other databases; thus, it can be an addition to existing initiatives of geological data collection. The aim of the REFLECT project is to provide a living database that can be updated with more data after the end of the project.`

4. Conclusions

The presented approach, methodologies, and results established in the REFLECT project are contributing to the closing of knowledge gaps related to geothermal fluids properties. With the downhole sampling approach, a technological challenge to assess superhot geothermal wells will be solved. This will extend the existing dataset to even higher temperature systems. REFLECT has brought together newly collected and analysed samples from geothermal sites with previously existing data to form the database for the European Geothermal Fluid Atlas, but also for a first database of organic compounds and microbes in geothermal fluids. These datasets can be used to rapidly assess the kind of fluids at a certain location, and thus permit an improved view of the associated risks when installing a geothermal power plant. They may also be used for predictive modelling to optimise plant layout and operations. However, predictive modelling may benefit not only from the improved datasets on natural geothermal fluids, but also from the data on physical and chemical fluid properties that resulted from the experimental investigations of synthetic fluids concerning degassing, precipitation, dissolution and biofilm formation. Finally, the improved and combined modelling approaches that have been developed in REFLECT allow the consideration of more parameters of the complex (geo-)chemical and engineering system of geothermal operations and improve the informative value of predictive models by including uncertainty propagation.

In conclusion, the knowledge and methods generated by the REFLECT project will enable solutions to improve the overall performance of geothermal energy production and reduce maintenance costs, and therefore to increase the economic viability and environmental sustainability of geothermal plant operations. Results of the project are published via scientific publications, but also factsheets, brochures, project deliverables and public presentations at scientific conferences and events of the geothermal community. All public material is available via the project website: ***www.reflect-h2020.eu***.

Author Contributions: Conceptualisation, S.R. and K.Ki.; methodology and analysis, D.C., M.M.D., F.E., P.J., A.K., K.Ko, J.M., A.P., A.S.M., A.S., S.O.V.; software, L.A. and P.S.O; writing—original draft preparation, K.Ki.; writing—review and editing, S.R., L.A., D.C., M.M.D., F.E., P.J., A.K., K.Ko, J.M., P.S.O., A.P., A.S.M., A.S., S.O.V.;. All authors have read and agreed to the published version of the manuscript

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Degassing kinetics of high salinity geothermal fluids

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The production of geothermal fluids can be adversely affected by the formation of free gas bubbles (degassing). Decreasing pressures can cause dissolved gas to exsolve, which can reduce water production. This study aims to improve the understanding of the conditions under which free gas nucleates in geothermal reservoirs. The focus is on CO_2 degassing from brines with varying salinity. We report a series of depressurisation experiments at high pressure and temperature using a cell that allows for visual monitoring of the degassing process using a high-speed camera along with pressure and temperature logging. A geochemical model was created for simulating the degassing behaviour at the same conditions as those used in the experiments, thus allowing for direct comparison.

La production de fluides géothermiques peut être altérée par la formation de bulles de gaz libres (dégazage). Des pressions décroissantes peuvent provoquer l'exsolution de gaz dissous, ce qui peut réduire la production d'eau. Cette étude vise à améliorer la compréhension des conditions dans lesquelles le gaz libre nucléée dans les réservoirs géothermiques. L'accent est mis sur le dégazage du CO_2 des saumures à salinités variables. Nous rapportons une série d'expériences de dépressurisation à haute pression et température à l'aide d'une cellule qui permet la surveillance visuelle du processus de dégazage à l'aide d'une caméra à grande vitesse, ainsi que l'enregistrement de la pression et de la température. Un modèle géochimique a été créé pour simuler le comportement de dégazage dans les mêmes conditions que celles utilisées dans les expériences, permettant ainsi une comparaison directe.

La producción de fluidos geotérmicos puede verse afectada negativamente por la formación de burbujas de gas libre (desgasificación). Las presiones decrecientes pueden hacer que el gas disuelto se disuelva, lo que puede reducir la producción de agua. Este estudio tiene como objetivo mejorar la comprensión de las condiciones bajo las cuales el gas libre se nuclea en los yacimientos geotérmicos. La atención se centra en la desgasificación de CO_2 de salmueras con salinidad variable. Presentamos una serie de experimentos de despresurización a alta presión y temperatura usando una celda que permite el monitoreo visual del proceso de desgasificación usando una cámara de alta velocidad junto con el registro de presión y temperatura. Se creó un modelo geoquímico para simular el comportamiento de desgasificación en las mismas condiciones que las utilizadas en los experimentos, lo que permite una comparación directa.

1. Introduction

Degassing has several implications in subsurface flow applications such as the production of hydrocarbons or geothermal fluids. Free CO_2 bubbles can cause more favourable conditions for the precipitation of calcium carbonate scale during both oil production [1, 2] and production of geothermal brines [3, 4]. Chemically active gases like CO_2 and H_2 can also cause corrosion in both oil and geothermal wells [5].

In exploration of geothermal sites, the presence of degassing is also used as a marker for the potential of the site to contain geothermal resources [6]. Surveys of CO_2 degassing in soils have been used for this purpose in particular [7, 8]. Furthermore, regions of high degassing rates are also found to indicate the presence of high-permeability faults [9]. Finally, the presence of free gas bubbles can also lead to reduction of the water relative permeability of the reservoir as the bubbles take up space, thereby limiting the ability for the water to flow. This was assumed to have happened in the Groß Schönebeck field in Germany, which led to a reduction in the production index [10].

This study aims to improve the understanding of the formation of free CO_2 bubbles from fluids during a depressurisation process, under geothermal reservoir conditions. The main research topic that is addressed is the dependency of the bubble point pressure on various parameters such as temperature and brine salinity.

2. Materials and methods

Experiments performed in this study focus on the formation of free CO_2 bubbles during depressurisation, mimicking the changes in pressure encountered in a geothermal well. The experiments were done at temperatures ranging from 40 to 150 °C. This temperature range implies that these experiments are representative of low enthalpy geothermal sites [11].

2.1. Experimental setup

The experimental setup depicted in ***Figure 1*** consists of the following components:

- A Vindum Engineering VP1-12K-HC dual piston aqueous phase pump allows for injecting water at high pressure.
- A Proserv Prolight 002990 titanium transfer vessel with a magnetic stirrer is used for creating gas-liquid mixtures.
- A titanium, high-pressure visual cell with two sapphire sight glasses (30 mm diameter) on either side to allow

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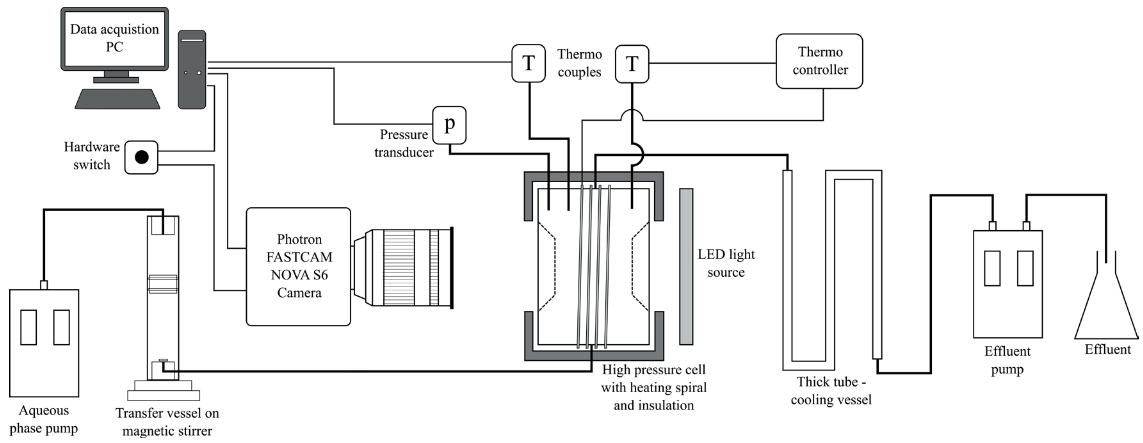
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Photron FASTCAM NOVA S6 Camera
LED light source
Effluent pump
Effluent
High pressure cell with heating spiral and insulation
Thick tube - cooling vessel
Aqueous phase pump
Transfer vessel on magnetic stirrer

Figure 1: Schematic of experimental setup.

for visualisation of the flow inside. The cell is cylindrical and has a 30 mm diameter and a depth of 10 mm. Fluid inlet and outlet are located at the side and top of the cell, respectively. A LED light source is installed to allow for uniform illumination of the cell's inner volume.

- A heating spiral is wrapped around the cell so that it can be heated up to the desired temperature in combination with a PID thermo-controller.
- A Photron FASTCAM Nova S6 camera is installed in front of the cell's window for high-speed imaging of the contents of the cell. This camera is used here at a rate of 500 frames per second. The camera is paired with a Laowa 100 mm f/2.8 2x Ultra Macro APO lens.
- A Sensata 84HP pressure transducer is connected to the cell to monitor the pressure during the experiments at a frequency of 100 Hz.
- Two thermocouples are connected to the cell as well: one for connecting to the thermo-controller and one to a data acquisition PC.
- A second Vindum Engineering VP1-12K-HC pump is used downstream of the cell in fluid receiving mode to reduce the pressure in a reproducible manner.
- Thicker tubing is installed downstream of the cell, which acts as a vessel for the hot fluids to cool down.
- A hardware switch is connected to both the camera and the data acquisition PC and is used to simultaneously stop the pressure and image recording, thus allowing for synchronisation between the two.

2.2. Experimental procedure

Brine and CO_2 are premixed in the desired proportions and pressure in the transfer vessel and then homogenised using a magnetic stirrer. The visual cell is initially filled and pressurised using the same brine. The initial pressure is based on the predicted bubble point pressure from the model and is chosen to be significantly higher than this value. The brine-CO_2 mixture can then be pumped from the vessel into the cell, displacing the initial brine in the cell. Five times the cell's volume of the CO_2-brine mixture is injected into the cell to ensure that the cell contains the correct CO_2 concentration. Next the cell is heated to the desired temperature. The CO_2-fluid mixture inside the cell is continuously monitored during both the filling and heating stage. Subsequently, the depressurisation is performed by letting the downstream pump receive fluid from the cell. The receiving rate is scheduled such that the pressure reduction rate is gradual. The full depressurisation process takes approximately 40 seconds to complete, which coincides with the time it takes to fill up the camera's memory buffer. Once the pressure has been reduced sufficiently, free gas bubbles will start to form within the cell. The pressure at which the first gas bubbles are observed is the bubble point pressure and this pressure is the main result that is analysed in this study.

2.3. Data analysis methods

The main results from each experiment are a set of images that show the emergence of bubbles during the degassing process and the accompanying pressure log. An image analysis routine was developed using the MATLAB Image Processing Toolbox to identify individual bubbles and their properties such as size and growth rate. Since the images captured during the experiment and the pressure log are synchronised, the bubble data from the analysed images are combined with the pressure data to determine at which pressure bubbles are formed during the degassing process.

The image analysis consists of the following steps: first the background image (i.e., the image at the start of the experiment before bubble formation) is subtracted, resulting in net images with bubbles showing up as regions of high intensity. These net images are then converted to a binary format. Individual bubbles are identified in these images using MATLAB's regionsprops function. Finally, the number of bubbles (i.e. individual regions) are counted on each image and can thus be plotted as a function of pressure.

2.4. Overview of experiments

Table 1 shows an overview of the experiments that were carried out within this study and lists their experimental conditions. Different brine compositions, temperatures and CO_2 concentrations were studied. For some of the experiments this means that CO_2 can already start forming bubbles while it is in its supercritical state, since the critical point is at: $p_{crit,CO2} = 73.8$ bar, $T_{crit,CO2} = 31.0$ °C.

2.5. Model description

This study mainly focuses on determining the bubble point pressure as a function of the studied parameters. The experimental results are compared to a geochemical model that predicts the solubility of CO_2 in brine. This model uses the R coupled version of PHREEQC [12]. PHREEQC (pH-REdox-EQuilibrium) is a software package for simulating chemical reactions and transport processes [13].

At low pressures and following Henry's

Table 1: Overview of experimental conditions for elevated temperature experiments.

Brine composition	*Temperature (°C)*	*Initial CO_2 concentration [mol/kgw]*
1 M NaCl	*40, 60, 100, 150*	*0.20*
1 M NaCl	*40, 60, 100*	*0.50*
1.5 M $CaCl_2$ + 2 M NaCl	*40, 60, 100, 120*	*0.15*

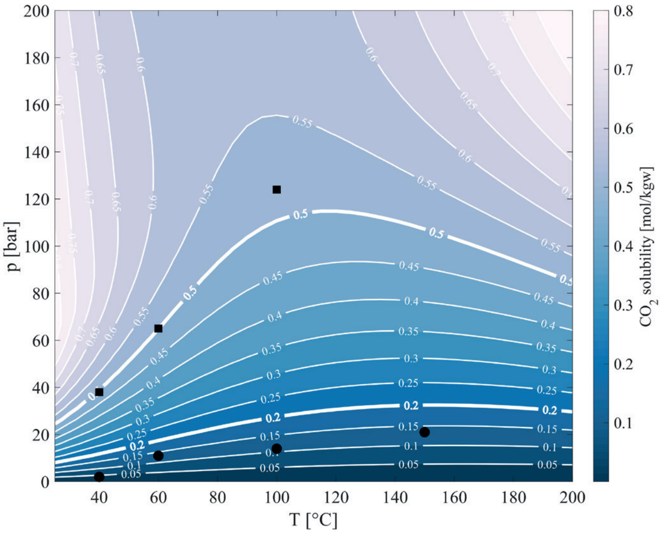

Figure 2: P-T dependence of the CO2 solubilities in a 1 M NaCl brine solution. Results are obtained with PHREEQC and CO2 fugacities computed using the Duan and Sun (2003) EoS. Experimentally obtained bubble points are also given for both the 0.20 mol/kgw (●) and 0.50 mol/kgw (■) CO2 concentrations.

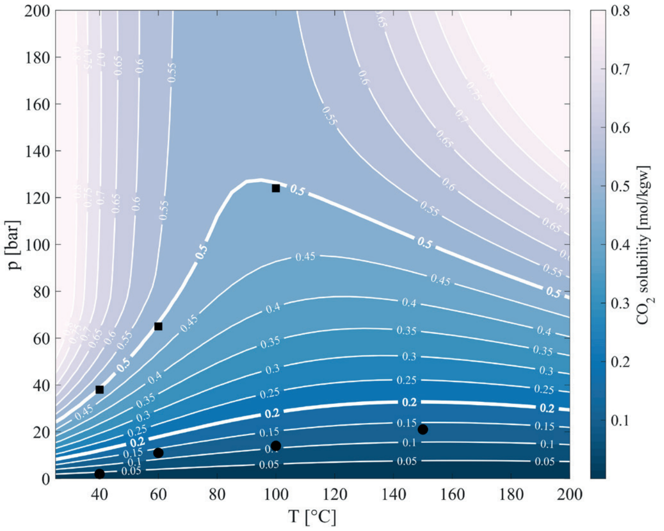

Figure 3: P-T dependence of the CO2 solubilities in a 1 M NaCl brine solution. Results are obtained with PHREEQC and CO2 fugacities computed using the volume translated SRK Eos. Experimentally obtained bubble points are also given for both the 0.20 mol/kgw (●) and 0.50 mol/kgw (■) CO2 concentrations.

law the molar fraction of CO_2 in the aqueous phase depends on the partial pressure of the gas phase ($P_{CO2(g)}$) divided by Henry's constant K_H:

$$x^{aq}_{CO2} = \frac{P_{CO2(g)}}{K_H}$$

For high pressures the partial pressure needs to be replaced by the fugacity:

$$x^{aq}_{CO2} = \frac{\phi P_{CO2(g)}}{K_H} exp\left(\frac{-v_{CO2}}{RT}(P_{CO2}-1)\right),$$

where ϕ is the fugacity coefficient of CO_2. This can be computed by an Equation of State (EoS: [14, 15] or any other variant of a cubic or virial EoS); the exponential term is often called "Poynting correction"; v_{CO2} is the partial molar volume of CO_2 (aq) averaged over the P range [1,P_{CO2}]. In the following, v_{CO2} is equal to 0.032 L/mol [16]. At specified pressure and temperature conditions the PHREEQC model requires CO_2 fugacities as an input, which were computed with individual EoSs.

3. Results and discussion

3.1. Comparison of experimental and modelled bubble points

Figure 2 shows the modelled CO_2 solubility in 1 M NaCl brine as a function of pressure and temperature with input CO_2 fugacities computed using an EoS described by [14]. The contours in the plot are iso-solubility (mol/kgw). Experimentally determined bubble point pressures for this same brine are given in the same plot for comparison for both the 0.20 and 0.50 mol/kgw CO_2 concentrations, which is why these contours are plotted using thicker lines. For the higher concentration experiments, the measured bubble points coincide fairly accurately with the predicted solubility, that is, the measurements are close to the 0.50 mol/kgw contour. This is not the case for the 0.20 mol/kgw experiment, where the measured bubble points are significantly lower than the model predicts. Measured bubble points here are between the 0.10 and 0.15 mol/kgw contours.

An even better fit to the high concentration experiments can be obtained by using another EoS. Here we use the volume translated version of the Original Soave-Redlich-Kwong (SRK: [17]) EoS as described by [18]. In this case, the EoS's parameter values are fitted to the experimental data to obtain an improved match between experiment and model, as shown in ***Figure 3***. Visual observation of the model prediction shows a better fit for the 100 °C experiment compared to the Duan and Sun EoS. Still, a good fit was not found for the lower concentration experiment, where data points remain significantly lower than the model predicts. The experimental approach can introduce a certain degree of error in the results, which may help explain the observed deviations between experiments and model. In order to assess the impact of the experimental approach, the experiments were first repeated using the same conditions. A comparison between the original and repeat experiments allows for determining whether the experimental procedure was carried out correctly as both experiments should ideally give the same results. Both sets of experiments were found to yield very similar results with variations in bubble point pressure limited to just 1 bar. Therefore, the experiments are considered to have been performed correctly. Secondly, the image analysis procedure was changed by lowering the threshold in the binary conversion step. This implies that smaller bubbles can be picked up earlier,

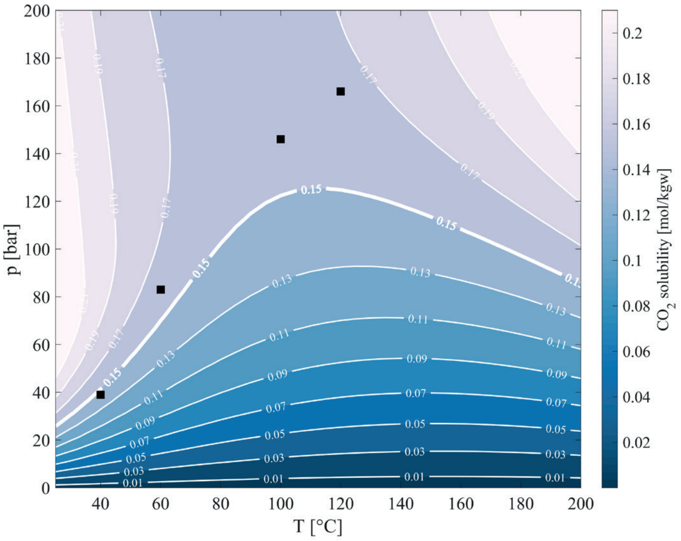

Figure 4: P-T dependence of the CO_2 solubilities in a 1.5 M $CaCl_2$ + 2 M NaCl brine solution. Results are obtained with PHREEQC and CO_2 fugacities computed using the Duan and Sun (2003) EoS. Experimentally obtained bubble points are also given for a CO_2 concentration of 0.15 mol/kgw (■).

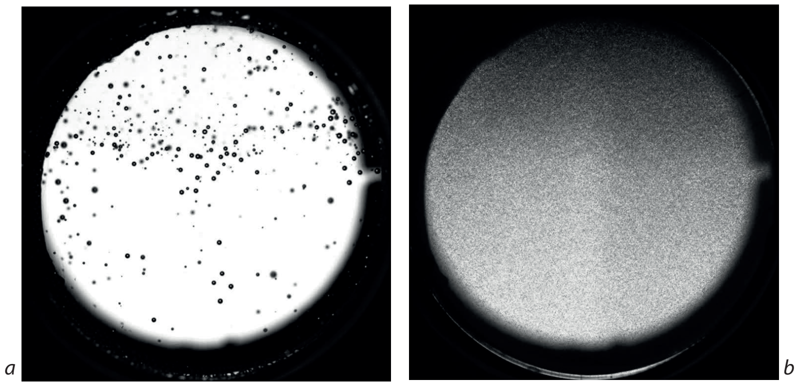

Figure 5: Experiments using 1 M NaCl brine and 0.5 mol/kgw CO_2 concentration showing (a) gaseous bubbles at 40 °C and (b) supercritical bubbles at 100 °C.

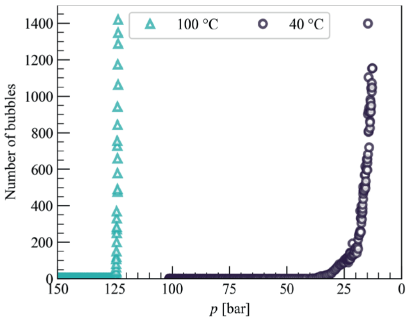

Figure 6: Number of bubbles vs. pressure for the experiments using 1 M NaCl brine and 0.5 mol/kgw CO_2 concentration at 40 and 100 °C, respectively.

but also that noise can erroneously be identified as bubbles. This still only caused very small deviations in the obtained bubble points, again with differences of around 1 bar compared to the values found earlier. So neither the repeat experiments nor the change in the image analysis are sufficient to explain the discrepancy between measurement and model prediction, requiring further investigation.

***Figure* 4** shows the model prediction of CO_2 solubility for the higher salinity brine (1.5 M $CaCl_2$ + 2 M NaCl) using the EoS of Duan and Sun along with the experimentally obtained bubble points using a CO_2 concentration of 0.15 mol/kgw. The lower concentration compared to the experiments using the 1 M NaCl brine was chosen here due to the model predicting significantly lower CO_2 solubility here. Results are thus compared to the 0.15 mol/kgw solubility contour, hence the increased line thickness for this contour.

Experimentally determined bubble point pressures found here agree reasonably well with the model predictions, although the deviations increase with increasing temperatures. The model also predicts increased CO_2 solubility for this concentration at temperatures beyond 100 °C. This behaviour was not found in the experiments, as the bubble point pressure at 120 °C is significantly higher than that at 100 °C. Additional experiments at higher temperatures are recommended to validate the model predictions.

3.2. Gaseous vs. supercritical bubbles

As mentioned above, some experiments performed here already have bubbles performing above the critical point of CO_2. This is especially true at higher temperatures and CO_2 concentrations. Figures 5a and b show the bubbles for the experiments using the 1 M NaCl brine with 0.5 mol/kgw CO_2 concentration at 40 and 100 °C respectively. At 40 °C, bubbles only start forming at a pressure of ~40 bar, which means that here bubbles are gaseous, as the pressure is below the critical point. This results in fairly large bubbles that quickly rise up through the aqueous phase. For the 100 °C experiment, the bubbles already start forming at a pressure of ~125 bar, which is above the critical point of CO_2, and thus bubbles are supercritical here. These bubbles are much smaller compared to the gaseous bubbles at lower temperatures, which causes them to be much less buoyant and not to rise as fast inside the cell. The rate of bubble formation is also much larger for supercritical bubbles, as shown in ***Figure* 6**, which shows the observed number of bubbles as a function of pressure. Almost all of the supercritical bubbles form instantly as the bubble point is reached, obscuring the entire visual window and thus making it hard to distinguish individual bubbles. The gaseous bubbles at lower temperatures form far more gradually, starting with only a few bubbles near the bubble point and then gradually increasing as the pressure is reduced further.

4. Conclusions and recommendations

- For the 1 M NaCl brine, the bubble point of a mixture with a high, 0.50 mol/kgw, CO_2 concentration, a good match is found between experiments and model for the investigated pressure and temperature conditions using either the Duan and Sun or volume translated SRK EoS model.
- At lower CO_2 concentrations, significant differences are found between the model and experiment. These deviations may be caused either by errors in the experimental approach or the model. Further evaluation of the degree to which these errors affect the results is recommended. The model description may also be improved by using pressure or temperature dependent formulations for certain physical parameters.

- The higher salinity brine (1.5 M $CaCl_2$ + 2 M NaCl) has approximately three times lower CO_2 solubility compared to the 1 M NaCl brine. A good match is found for experiment and model for this brine using a CO_2 concentration of 0.15 mol/kgw, although deviations between experiments and the model increase at higher temperatures.
- Supercritical bubbles are much smaller and also form in much greater numbers at or near the bubble point pressure compared to gaseous bubbles.
- Further experiments at higher temperatures are required to validate the solubility behaviour that is predicted by the geochemical model. The experimental approach (i.e., high-speed imaging inside a visual cell) used here is well suited for performing experiments at higher temperatures, although some parameters can be improved upon to capture the process in greater detail. These include running the camera at a higher frame rate and using a more zoomed-in view of the visual cell. This is especially relevant when observing the formation of the supercritical bubbles, which are very small and form almost instantaneously in large quantities.

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News corner:
Compiled by Anita Stein, EFG Office

Award of the EFG Medal of Merit to two outstanding geologists: Marie Fleming and Fernando Noronha

During its spring 2022 meeting, the Council of the European Federation of Geologists (EFG) decided to award its Medal of Merit (MoM) to both EurGeol Marie Fleming and Prof. Fernando Noronha, nominated respectively by the Institute of Geologists of Ireland (IGI) and by the Portuguese Association of Geologists (APG). The EFG Medal of Merit is awarded to individuals who, in the view of Council, have provided exceptional and distinguished contributions to the EFG or to the geological profession in Europe. The official award ceremony took place in Brussels, on 19 November 2022, at the occasion of the 81st EFG Council meeting.

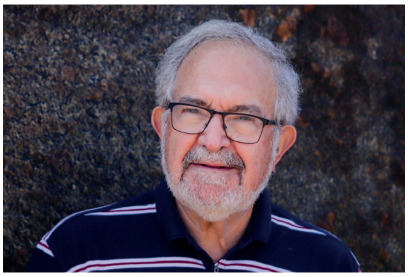
Marie Fleming graduated from University College Cork in 2000 and obtained her MSc in Engineering Geology from Imperial College London in 2006. She is a chartered engineering geologist with Arup and an industry advisor and visiting lecturer in Engineering Geology at several universities.

Marie Fleming is a Past President of the Institute of Geologists of Ireland (IGI) 2015-2017, Chair of the Registration Authority of the European Federation of Geologists from 2013 to 20210 and a member of the External Relations Committee of the Geological Society of London from 2014 to 2020. She has been a Trustee of the charity Geology for Global Development since 2018.

During the award ceremony, Marie Fleming stated, “Being part of the EFG has been huge for me. It’s been an amazing 10 plus years of companionship, of collaboration and of working with the common goal of trying to provide a unified voice for geology across Europe.”

The award has been proposed by IGI due to Marie Fleming’s long term of office and her intimate knowledge of the EFG Statutes and Regulations, coupled with advice given to the Board and Council in line with those Statutes and Regulations.

Professor Fernando Noronha is an outstanding geologist known both nationally and internationally for his notable work and research, mainly on economic geology, characterisation of geological materials, granite related ore deposits, hydrothermal fluids, tungsten deposits, Li-pegmatites and Variscan magmatism, but also in geological processes, field and exploration geology, geological mapping, tectonics and geodynamics, geodiversity and geoheritage and science communication, to name a few. Professor Noronha is a past-President of the Portuguese Association of Geologists (APG), having served the association as President from 2002 to 2008. He was also an EFG delegate, representing EFG and its values and mission during this time.



APG proposed the award due to Fernando Noronha’s life dedication and service to geology and to the profession of geology.

In his speech, Professor Noronha underlined that “The role of EFG and its national associations are extremely important and it is fundamental for geologists to be heard and recognised by society and policy makers.”

Congratulations to Marie Fleming and Fernando Noronha!

EFG President Marko Komac with the awardees Marie Fleming (left) and Fernando Noronha.

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The European Geologist journal publishes feature articles covering all branches of geosciences. EGJ furthermore publishes book reviews, interviews carried out with geoscientists for the section 'Professional profiles' and news relevant to the geological profession. The articles are peer reviewed and also reviewed by a native English speaker.

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- Deadlines for submitting article proposals (title and content in a few sentences) to the EFG Office (***info.efg@eurogeologists.eu***) are respectively 15 July and 15 January. The proposals are then evaluated by the Editorial Board and notification is given shortly to successful contributors.
- Deadlines for receipt of full articles are 15 March and 15 September.

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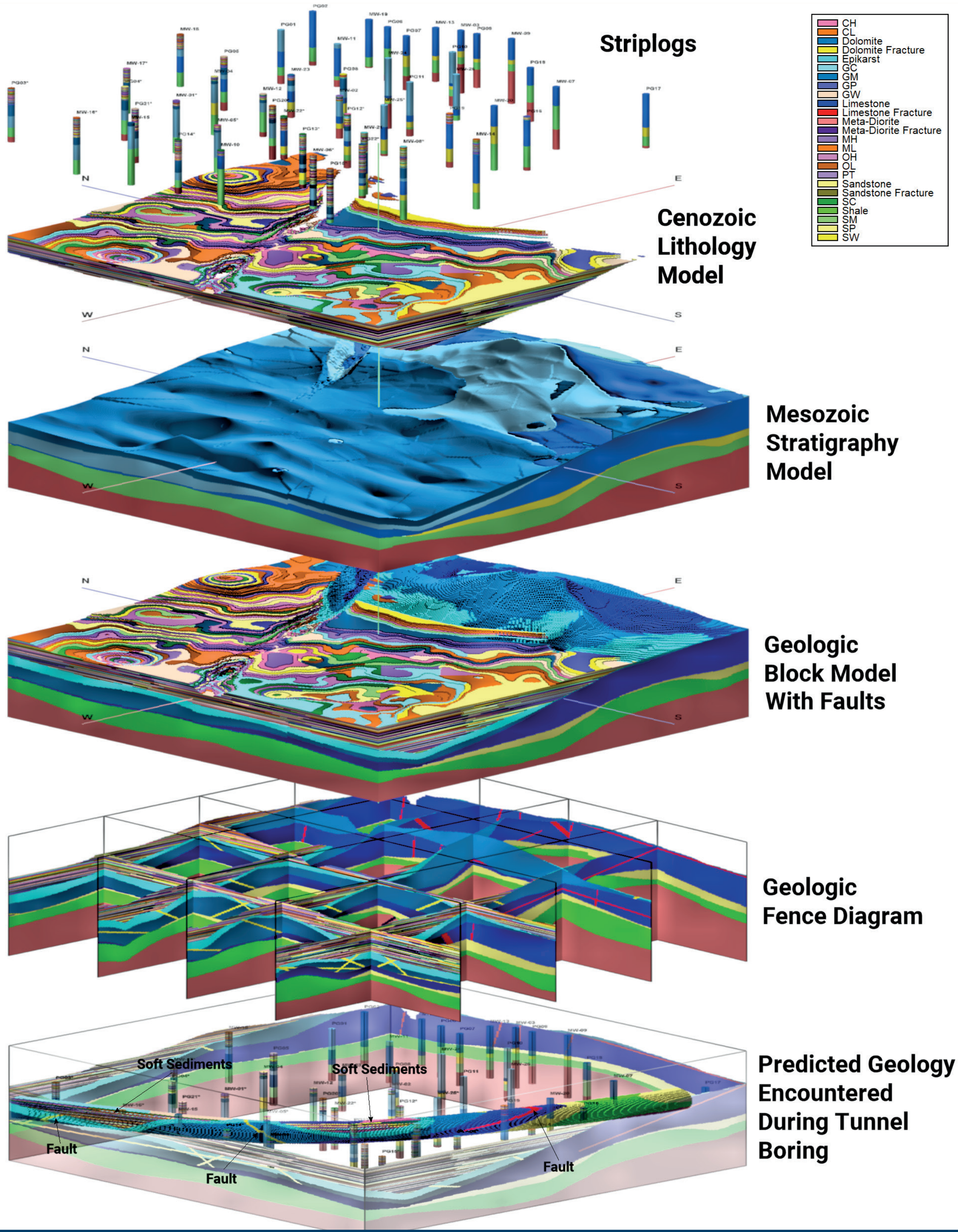

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